545: Sunlight control in Galleries through dynamic inter-reflection

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Abstract

Daylight and sunlight plays a central role in the lighting strategies for art galleries, often through the application of dynamic roof-lights. This paper assesses the viability of a roof-light system which uses dynamic inter-reflection of sun-light to provide diffuse light at an acceptable day-light factor suitable for the luminous environment of a gallery space. The performance of the system is assessed through theoretical models, and quantitatively measured through a series of experiments. The potential strengths and weaknesses of the system is explored in terms of its application to design.

Keywords: Innovative Materials, Components and Systems

1.0 Introduction

In the context of a top-lit gallery space, a roof-light functions as an 'interface' between external and internal luminous environments. This 'interface' must mediate between varying external illuminances and the more controlled internal illuminances which are required for the display and conservation of art [1]. In addition to the intensity of light, the quality of light in terms of diffusion and colour rendering are critical. There are a myriad of roof-lighting systems in operation in galleries across the world designed to achieve this 'interface' through the use of dynamic louvres / blinds [3]. This paper explores the viability of a roof-lighting system which mediates between the internal and external lighting environments through the use of inter-reflection alone.

2.0 Design hypothesis

2.1 Lighting control through inter-reflectance

When light hits a surface, depending on the colour of that surface, a proportion of that light will be absorbed and a proportion re-reflected [2]. Assuming the reflectance of that surface is specular, the angle of reflectance will be equal to the angle of incidence relative to the normal. Therefore in a situation where light is inter-reflected between two specular surfaces, then for each inter-reflection, the direction and intensity of the re-reflected light may be calculated. Figure 1 illustrates this arrangement with two parallel surfaces of an assumed reflectance of 0.5. In this instance, if a 77.5% reduction in light levels was desired, (in other word a 12.5% daylight factor), then 3 inter-reflections would be required.

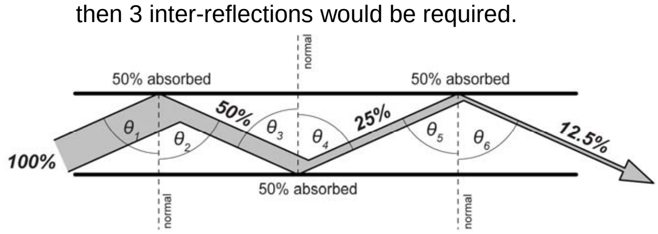


Fig. 1: Direction and intensity of light reflected between two specular planes

The number of inter-reflections required to achieve a desired output light level is dependant on the reflectance of the surfaces. Figure 2 shows this relationship for a range of reflectances, to achieve an illuminance drop from 20 klux to 100 lux. For a very low reflectance of 0.1, only two inter-reflections would be required. For a reflectance of 0.3, up to eight inter-reflections would be required.

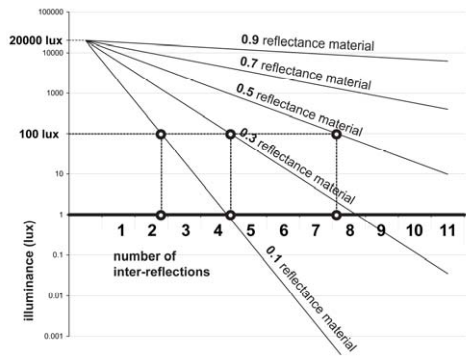


Fig. 2: Reduction in light levels for different reflectance materials.

A roof-light which can dynamically control the number of inter-reflections should therefore be able to provide a useful way of 'interfacing' between the external luminous environment and the internal luminous environment of a gallery.

2.2 The Vault as a diffuser of light

Multiple inter-reflections offer the potential to reduce illuminance levels however, diffusion of light is also highly desirable in the context of a gallery. A curved reflecting surface, such as a vault, acts as a natural diffuser of light. When sunlight hits the curved surface of a vault, the range of incidence angles will result in an equivalent range of reflected angles. Where a series of vaults are used in combination the inter-reflections of light between the surfaces will create multiple light diffusions within the geometry, meaning that the output light, rather than showing the input light source, will instead produce a diffused light (Figure. 3)

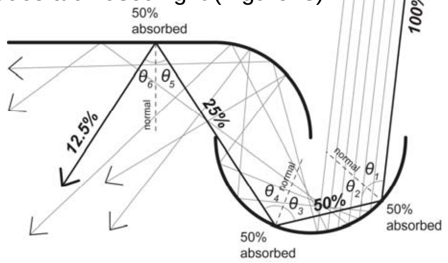


Fig. 3: Diffusion of sunlight using multiple vaults.

2.3 Dynamic movement of multiple vaults

Controlling inter-reflections with respect to inter-seasonal / daily variations in solar altitudes and azimuths requires a dynamic movement within the vaults.

Figure 4 shows how in a fixed arrangement the number of inter-reflections within the geometry varies according to the altitude of the sun. For high solar altitudes, the steep angle of incidence allows light to pass through the vault configuration with two inter-reflections. This should result in a high day-light factor however, given that the width of the aperture relative to the angle of the sun is very narrow, this means that at these times less light will enter the system (a). For low altitude angles, the shallow angle of incidence and reflectance mean that up to 4 – 5 inter-reflections are required within the geometry. However, in this case, far the width of the aperture relative to the light is far wider, meaning that although more inter-reflections are required, in fact, more light will pass through (b).

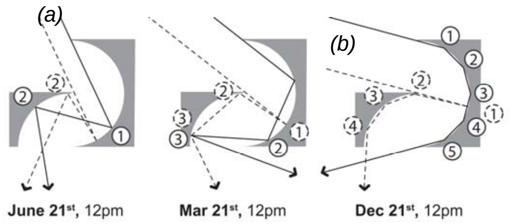


Fig. 4: Inter-reflections in a fixed multiple vault geometry for solstice and equinox zenith solar positions

By introducing a pivot into the vault geometry, the relative angle of the geometry can track that of the sun throughout the year. This has the double advantage of maintaining the relative width of the aperture to the light source, and also controlling the number of inter-reflections within the vault for a range of solar altitudes. Figure 5 shows most light passes through the system with 3 or 4 inter-reflections. Assuming a surface reflectance value of 0.5, this would equate to a daylight factor of around 12.5%.

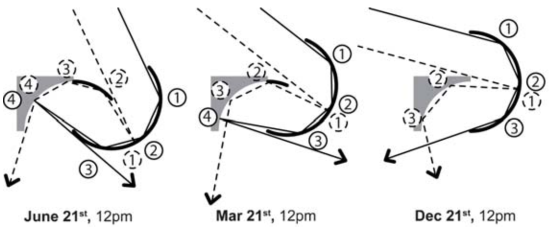


Fig. 5: Inter-reflections in a dynamic multiple vault geometry for solstice and equinox zenith solar positions

Although the proposed movement would control inter-reflections for the zenith position, clearly providing a dynamic movement to respond to non-zenith would clearly be a far more complex task. Therefore in the interests of simplicity, only the zenith positions are considered here.

3.0. Physical Testing

3.1 Objective

In order to understand how the system might work in reality, a physical model of fixed and dynamic multiple vault roof-lights were constructed, and tested for three solar positions, winter and summer solstices, and spring equinox for the zenith position only.

3.2 Methodology

A black lined box was constructed on to which three different roofs vaulted roof-lighting systems were fitted. Two lux meters were integrated into the box, and a camera fitted to one end. The model was mounted on a heliodon, set to the latitude of London. A light projector was used as a light source, and was positioned at a fixed distance from a heliodon on to which the light box was attached. A third lux meter was fixed at the roof-light aperture to measure external illuminances. Three different geometries were tested: (a) Fixed double vault (b) Fixed triple vault (c) Dynamic double vault. Lighting conditions inside the box were photographed for light levels were also recorded at fixed points inside and outside the text box, and the daylight factor within the box calculated in each case. In order to investigate the impact of materiality within the system, three different colours were tested; black, orange and white with reflectance values of 0.1, 0.5, and 0.9 respectively.

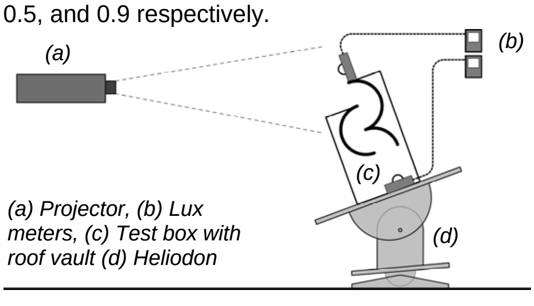
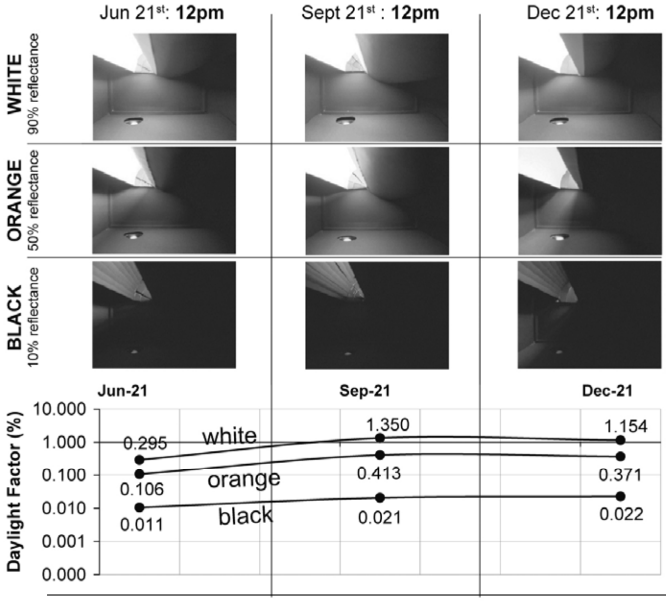


Fig. 6 Equipment used for physical experiment.

It should be noted that one critical difference between the theoretical and modelled tests was the reflectance of the vault linings. In the theoretical model, the surface was considered specular, allowing the accurate mapping of inter-reflections within the system. In the physical model however, the lining of the vault was lined with coloured paper which produced diffuse rather than specular reflections, and therefore resulting in far more numerous inter-reflections within the geometry. As a consequence far lower light outputs was expected than those predicted in the theoretical model. However the physical model allowed a useful quantitative and qualitative assessment of the lighting conditions using multiple vaulted roof light geometries.



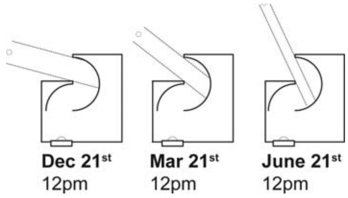
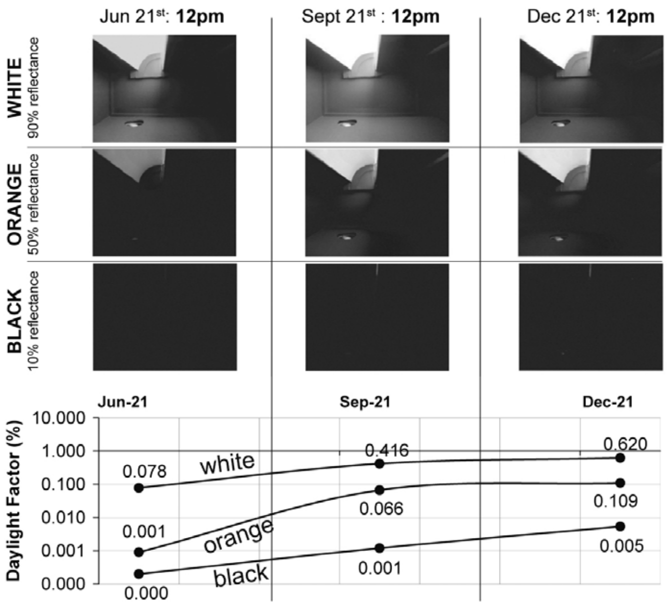


Fig. 7: Inter-reflections between a fixed multiple vault geometry for solstice and equinox zenith solar positions

3.3 Fixed Double Vault

The fixed double vault configuration shows variation of internal illuminances for different months, which is probably more a result of the aperture width relative to the light source than it is for varying inter-reflections within the geometry. However, in terms of the level of diffusion noted from the visual assessment of photographs, a more diffuse light is noted within the December setting than in the June, which is indicative of greater more inter-reflections within the system.



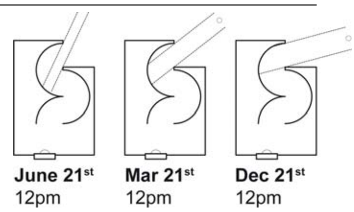
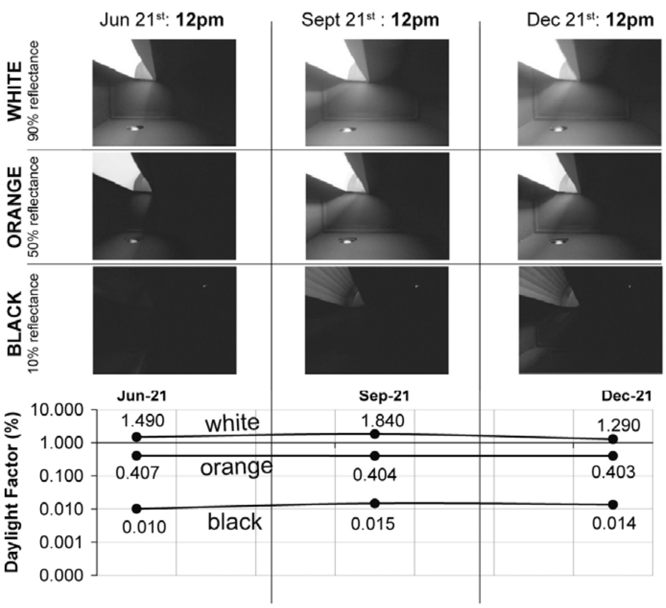


Fig. 8: Inter-reflections between a fixed multiple vault geometry for solstice and equinox zenith solar positions

3.4 Fixed Triple vault

The addition of a second vault to the roof light configuration impacts both light levels and the diffusion of light within the space. Again the difference between light intensity within the geometry may be attributed to relative aperture width rather than drop in illumination from inter-reflection. With the higher reflectance linings, a range of daylight factors from 0.08% to 0.62% is noted. In all cases the light within the test box is significantly more diffuse that in the fixed double vault geometry, with the December setting achieving the most diffuse light.



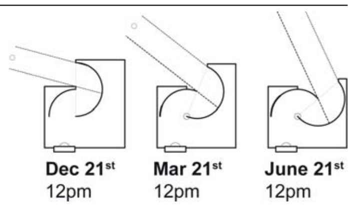


Fig. 9: Inter-reflections between a fixed multiple vault geometry for solstice and equinox zenith solar positions

3.5 Dynamic double vault

The addition of a dynamic movement to the system to track the solar altitude maintains the width of the aperture relative to the light source. For all reflectances tried, the daylight factor profile is similar for the three different solar positions tested, with a variation of only 0.55% DF as opposed to 0.86% for the fixed version. Diffusion of light is also more consistent across the three settings.

4.0 Application to design

The use of multiple vaults in a roof lighting situation can potentially generate a number of interesting architectural ideas. Fig. 10 shows a number of fixed double vault geometries, including a single fixed module, and an arrangement of multiple fixed modules. Both these designs prohibit a direct view to the sky, and will guarantee a reduction in light levels as a result of inter-reflections between the vaults. This will also improve diffusion within the gallery space. Both systems however suffer from the short-comings of a fixed system as already noted in this paper.

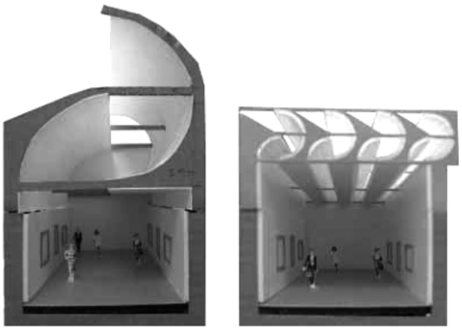


Fig. 10, Study models for fixed multiple vaults.

Fig. 11 shows a more complex arrangement of fixed and variable roof-lighting modules. Three different gallery spaces are considered each, with a different configuration and proportion of fixed and dynamic roof-light which will produce a different quality of light within the gallery. Galleries A with more generous aperture widths relative to the height above the gallery floor will have the highest illuminance levels. A dynamic roof light system will offer some inter-seasonal control. Gallery B, has narrower aperture widths, and is as a higher space will produce lower illumination levels on the display walls. Gallery C, illuminated through a roof light comprising five fixed vaults will provide a far lower illumination levels, and far more diffuse light perhaps more suited to the display of more sensitive art.

5.0 Conclusions

The viability of this roof-lighting proposal must be assessed in terms of the level of control if offers in terms of 'interfacing' between the internal and external luminous environments. It has been shown that for certain solar positions, a multiple vault configuration has the potential to provide controllable daylight factors, and good levels of light diffusion. Introducing a dynamic movement to the system goes some way to regulating inter-reflections within the system, and as such increases the level of inter-seasonal control. The system also offers an interesting starting point for architectural development of a roof-light strategy.

However there are some basic shortcomings which should be noted. Firstly, considering day-light factors alone can be misleading. What is important in the context of a gallery space is not the relative drop in illumination from inside to outside, but the absolute amount of light that falls on the art on display. As such although the multiple vault system may be able to theoretically achieve a 1% daylight factor for all seasons, the actual illumination within the space may differ radically with different sky conditions. Secondly, by examining only three times of the year, with the sun at its zenith at all times, the dynamic movement proposed fails to control inter-reflections for all other solar angles. Developing a dynamic movement which could control inter-reflections outside of these times would require an extensive system of movement and a level of complexity which is probably not justifiable. These basic short coming suggests that the system would be unable to achieve the kind of control required in a gallery situation throughout the day without complimentary artificial lighting to compensate for the inevitable variations in internal illuminances.

6. Acknowledgements

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7. References

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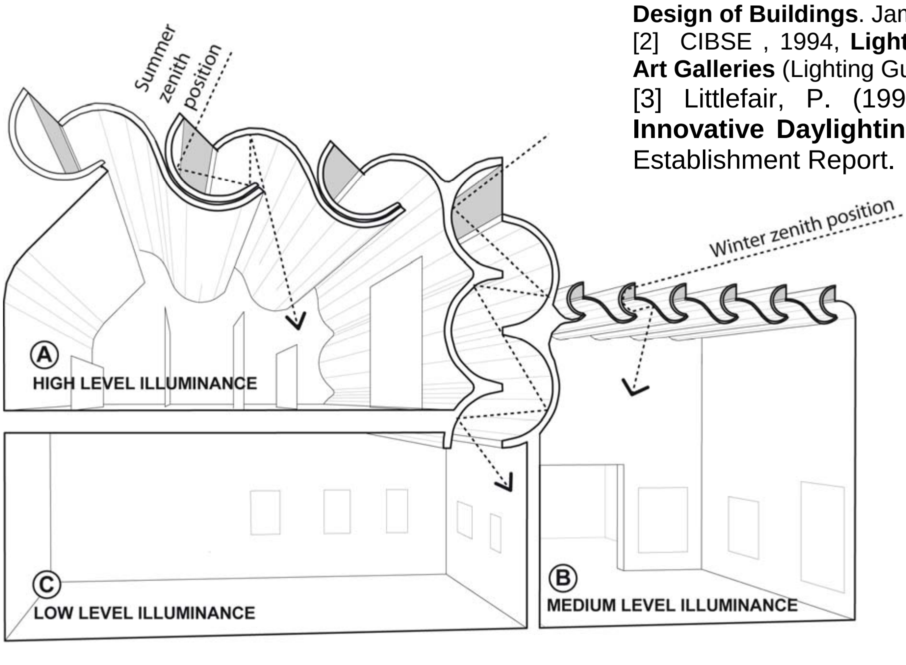

Fig 11: design proposal incorporating a series of fixed and dynamic roof-lights.