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Use of diffusers materials to improve the homogeneity of sunlight under pergolas installed in road tunnels portals for energy savings

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ABSTRACT

In spite of the benefits of shifting the threshold zone of road tunnels by means of pergolas, installed before their portal to save energy in the electrical lighting, the lack of uniformity in the road under these structures makes them a non accurate solution in terms of visual performance and, hence, road safety. In this work, a new solution, consisting on the introduction of a diffuser material in the spaces between beams of the pergola is proposed. The measurements and results in a scale mock-up, a computational simulation and the comparison with a theoretical model, as well as the potential impact in real tunnels are presented and analyzed.

1. Introduction

The most consuming installation in road tunnels is the electrical lightning, which must work 24 h a day, 365 days a year. Surprisingly, the energy cost associated with lighting during the daytime is much higher than during the night. This is due to the necessity to keep very high levels of illumination in the first part of the tunnel (the so called threshold zone) to allow a smooth visual adaptation of drivers coming from bright environments.

The threshold zone starts just at the entrance of the tunnel. It is extended from the portal towards the interior of the tunnel at least in a length equal to the safety distance (SD) (CIE Publ. 88, 2004). It is the most consuming zone in terms of energy in the whole tunnel. Once the driver is inside the tunnel, his eyes need to get used to a progressively darker environment. Hence, the lighting level in the threshold zone decreases from a given value of luminance (luminous flux per unit of solid angle and surface in one given direction) in its first half, L_{th}, up to $0.4L_{th}$ at the end of this zone. After this zone, the luminance in the tunnel will go on decreasing up to much lower values. Therefore, in the context of road tunnels, the threshold zone is the most important one from both, lighting and safety, points of view.

In order to save energy in the lighting of road tunnels and taking advantage of the daylight, two general solutions can be adopted: introduce the natural light into the tunnel (Gil-Martín et al., 2014) or shift the threshold zone out of the tunnel.

Concerning this last solution, several strategies have been proposed: in (Gil-Martín et al., 2011; Peña-García et al., 2012) the effect of placing a semi-transparent tension structure from both, real measurements in a tunnel and virtual models respectively has been studied. These structures have proved to be useful for this energy saving purpose.

Another way to shift the threshold zone out of the tunnel is by setting a pergola just before the portal gate of the road tunnel (Peña-García and Gil-Martín, 2013). The pergola can consist of a sequence of structural beams that hold the upper superstructure, this is the case in the intersections of two highways at different levels. It can be also a concrete vault with openings built in the portal gate of road tunnels. Whatever the shape of the pergola, light distribution on the road under the pergola consists on a succession of bright-shadow zones that may be uncomfortably to drivers.

In previous research (Peña-García and Gil-Martín, 2013), it was shown that, although the required average illuminance (luminous flux per unit of road surface) on the threshold zone, E_{av} , can be reached by setting pergolas at the entrance of the tunnel, the values established in road regulations related to illuminance uniformity, U_0, are not satisfied (Fig. 1). This illuminance uniformity is defined as follows:

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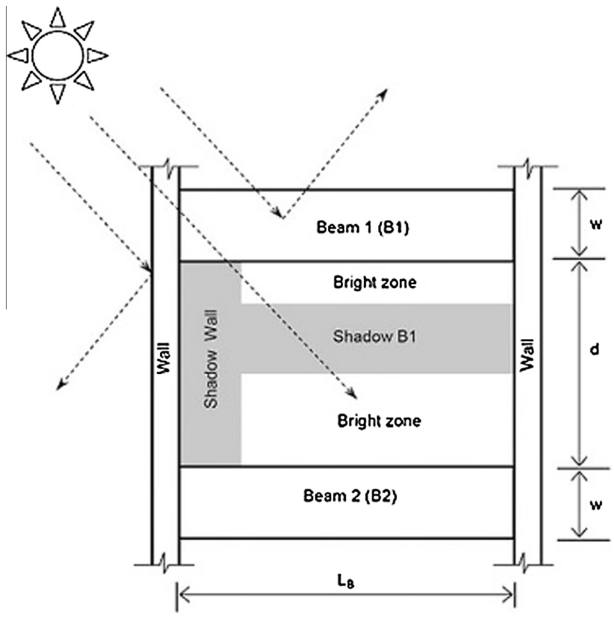

Fig. 1. Light distribution under one pergola. Image from (Peña-García and Gil-Martín, 2013).

$$U_0 = \frac{E_{min}}{E_{av}} \quad (1)$$

where:

E_{min} is the minimum illuminance measured on the road under the pergola.

E_{av} is the average illuminance measured on the road under the pergola.

According to (CIE Publ. 88, 2004), the illuminance uniformity in road tunnels must be higher than 0.4 (i.e. $U_0 > 0.4$) whereas, in the case of pergolas, there are zones of the road under the pergola in complete darkness (see Fig. 1) for which $E_{min} = 0$ (and thus, according to (1): $U_0 = 0$).

To overcome the lack of uniformity associated with pergolas in road tunnels, the effect of diffuser boards set in the gaps between the pergola beams have been studied. To achieve reliable results, measurements in a scale mock-up, computational simulations and a theoretical model have been used. These results have been compared, showing an excellent agreement and proving that the chosen diffusers remarkably improve the illuminance uniformity under pergolas. Then, these illuminance values have been introduced as input of the ESTS equation (Energy Savings under Tension Structures), demonstrating that the energy savings are also outstanding. All these results are analyzed and presented.

2. Materials and method

The choice of the diffuser material to cover the gap of the pergola was based on several criteria. This material must have high light transmission as well as high resistance to UV light and weathering and be affordable. Its surface hardness must be high enough to assure a long service life, which is very important in order to reduce the maintenance cost in roads. Although there are available several materials that satisfy the former requirements such as PC (polycarbonate) and other. In this study, a grainy acrylic resin (Polymethyl methacrylate, PMMA, see Fig. 2) has been adopted because it is 100% recyclable and therefore its environmental cost is very low.

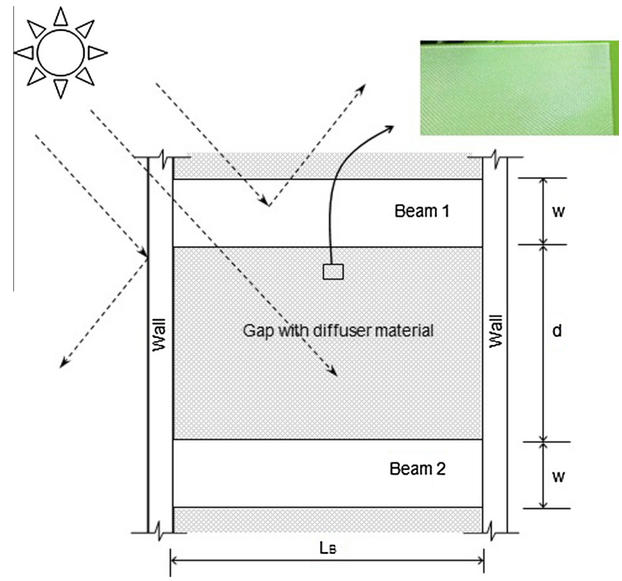

Fig. 2. Pergola with diffuser material in gaps and picture of a sample of grainy Polymethyl methacrylate (PMMA).

The aim of setting a diffuser material in the gaps is to spread light and illuminate the shadow zones that appear when a regular pergola is installed before the portal gate of the road tunnel (Fig. 1). The used material must be able to both, spread the light in all directions and decrease the level of lighting intensity on the road.

The grainy PMMA sample has a luminous transmittance (luminous flux transmitted by unit of length) of 90% for a 3.2 mm (0.125″) thickness sample. These data were supplied by the manufacturer.

The choice of PMMA responds to its accurate optical properties, its capability to be injected (that makes possible the grainy that diffuses the light) and also to its reasonable price.

A mock-up (scale 1:25) of a road tunnel with a pergola set before the portal gate has been used (Fig. 3). The entrance of the tunnel was aligned towards the North using a compass. In order to model a long tunnel, the exit was covered with a curtain of black velvet that prevented light to pass.

Although the mock-up incorporates a halogen light source with an spectral distribution very similar to the sun, it was decided to transport it to an open air area in order to take the measurements in real sun conditions.

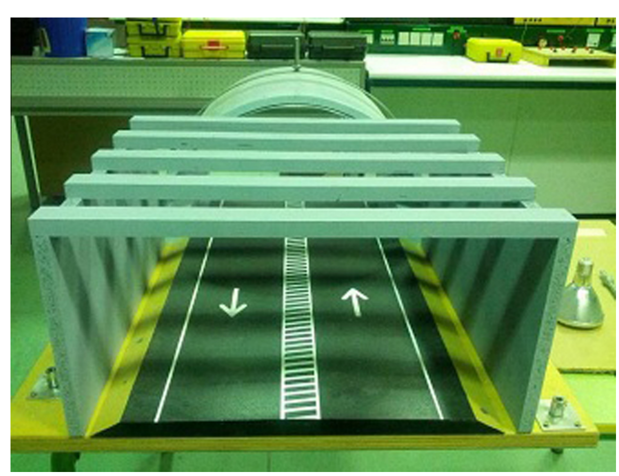

Fig. 3. Mock-up of the scaled pergola before the tunnel portal gate.