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Original article

Fire safety in Italian-style historical theatres: How photoluminescent wayfinding can improve occupants' evacuation with no architecture modifications

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ABSTRACT

Architectural Heritage is often prone to fire risk especially when many significant wooden structures with a particular historic and artistic value are present. This is the case of the Italian style historical theatres. Increasing fire safety of this architectural heritage generally clashes with preserving the original building features: massive and irreversible interventions are often needed so as to respect current severe regulations. Moreover, upgrading interventions can be insufficient so as to effectively improve occupants' safety level, especially in overcrowded spaces and when people do not know much of the building itself. Occupants' safety depends on their behaviours and their possibility to rapidly evacuate to a safe place. One of the most effective ways to help them to achieve this aim seems to be the adoption of a good emergency evacuation wayfinding system, especially in smoke or black-out conditions. This paper analyses the effectiveness of a reversible, easy-to-remove and low-impact system for evacuation guidance based on photoluminescent materials (PLM). The proposed continuous wayfinding system (CWS) is composed by PLM tiles along evacuation paths (both corridors and stairs). The application to a case study, the Italian style historical theatre "Gentile da Fabriano", is then provided. Tests involve more than 100 individuals in smoke and black out conditions. CWS effectiveness was compared to a traditional punctual system in terms of motion speeds (for single pedestrians) and total evacuation time (for the whole building evacuation drill). Questionnaires filled in by involved pedestrians qualitatively evaluated the individuals' acceptance of CWS. Tests with CWS show that individual's motion speed rises up to 50% and the total evacuation time is reduced down to 25% in respect to the traditional system. Comparisons with previous studies on PLM signs are provided. CWS can be easily introduced in this kind of historical theatres so as to increase the occupants' safety level.

1. Research aim

Architectural heritage (and in particular these historical theatres) is generally characterized by high risk levels in relation to buildings features (e.g. fire vulnerability of structural and non-structural elements such as wooden structures), potential fire sources (e.g. hazard connected to housed activities; malfunctioning of old electric plants) and general significant density of occupants that can be often stranger to architectural spaces. Inemergency conditions, people safety mainly depends on the possibility to evacuate the building in a correct way. Therefore, space perception and human choices in evacuation massively depend on the historical buildings layout and on guidance systems availability. For this reason, we are aimed at providing tools to evaluate risks for people in historical buildings and to design interventions that could jointly increase the safety level for building occupants and preserve the original heritage features. These issues firstly need the investigation of interactions between occupants and environment in emergency conditions, and in particular, in the evacuation phase. Understanding and analyzing human behaviors can provide not-invasive solutions for occupants' safety. This paper starts from this point of view, involves the application to the fire evacuation safety in significant kind of historical buildings (historical Italian-style theatre), and provides an evaluation about innovative concepts of emergency wayfinding elements.

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2. Introduction

Fire risk in Architectural Heritage is a significant issue, especially in case of wooden structures [1,2]. Besides, reduced places and high density of occupants characterize many historical buildings and this increases their fire risk as well as the fact that occupants are often unfamiliar with the building spaces.

In case of fire, people's safety mainly depends on the possibility of evacuating the building in the shortest time [3,4]: for this reason, occupants should be properly guided during their emergency motion towards right paths and exits. Current regulations are mainly based on dimensional requirements (width, length) of evacuation paths and exits [5–7]. As a consequence, this could mean introducing massive and invasive modifications to the original architectural features (e.g. introducing fire stairs, opening new doors and exits, defining different fire zones, building fire proof walls). Hence, regulations denote a schematic approach in building layout and do not consider the effective human behavioral aspects at all [8], for both not-disable and disable individuals [9].

A more respectful approach, which is oriented to both fire scenario definition and human behaviors analysis to provide not-invasive solutions for occupants' safety so as to preserve the architectural characteristics of the involved building, is thus desirable. This goal could be reached by taking advantages of the recent European fire safety guidelines [10]. They introduced the performance-based fire safety engineering design of buildings, which mainly includes the estimation of the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET) [3,10]. The egress of all building occupants has to be performed in conditions of not-exceeded tenability criteria in the building itself (ASET > RSET) [10]. ASET is operatively estimated through the evaluation of time-concentrations curves for toxic products, smoke and heat in a fire: its quantification involves the development of scenario modifications, and it is essentially based on fire characteristics (including its spreadings) and building features [3,11]. RSET estimation is founded on human behaviors and interactions between man and the surrouding environment [8]. RSET includes actions perfomed during pre-movement phase [12] and effective motion phase [4].

Whereas new buildings should be designed according to ASET/RSET relation, substantial fire safety problems in historical buildings [1,9,11] could be significantly reduced by applying the related desing criteria, especially in case of public buildings with high occupants' density. In particular, RSET could be minimized while preserving the original building features and so its cultural, artistic and architectonical values.

Many studies demonstrate how the use of efficient wayfinding systems could significantly decrease the occupants' egress time [13–15] and so RSET, avoiding massive interventions on buildings. They represent the easiest and most effective way to assist occupants. They can guide them during the evacuation process especially in particular environmental conditions (e.g. darkness, smoke) or when people are not familiar with the building [16]. Wayfinding signs must provide an immediate identification of escape routes and exits and guarantee a quick comprehension of all that information they make available in different environmental situations. Following these statements, the needed time for the best evacuation paths choice should decrease and the evacuation process in terms of motion speeds should also accelerate [17]. Safe condition signs and exit signage systems include: reflective signs [18], photoluminescent (PLM) signs [19–21], electrically-illumined signs [18], interactive wayfinding systems [22], acoustic wayfinding systems [23]. The related effectiveness is influenced by pedestrians' perception in relation to signs position and environmental conditions [8]. The accurate design of evacuation facilities layout (including plan positions and elevation from the ground) cannot exclude investigations on their use by the pedestrians. Experiments about identification distance [17,24] and influence on motion in terms of total evacuation time and speed [25,26] are performed so as to define the wayfinding systems effectiveness. In particular, when signs (mainly: low placed exit signs) are clearly visible (e.g. electrically illuminated, PLM) in smoke conditions, people statistically tend to follow their directional indications and to use the suggested shortest evacuation paths [14,27]. Evacuation drills in buildings are performed [4,28,29], and they can be supported by direct questionnaires on the involved individuals [12,28,30], so as to evidence singular aspects in appreciation of signs. Only a limited number of studies involve a high number of individuals [31,32] and current literature evidences a lack of data about historical buildings.

The most robust wayfinding systems is composed by PLM signs [26,33,34] because:

- they do not need any supply (no interventions on building structure and layout);
- they are easy-to-apply and easy-to-remove especially in case of adhesive elements;
- they need a low level of maintenance;
- they are efficient and useful in both light-on and black-out conditions.

Requirements of PLM signs are also defined by regulations [19,21]. Existing buildings scenarios are tested and demonstrate that PLM signs are able to guide the occupants towards the correct exit and to increase their evacuation speed in both corridors and stairs [26]. Wayfinding systems are mainly divided in continuous (at least 1 directional sign per 5 m of path) and punctual (mainly placed at intersections and exits) applications [35,36]. Applications on existing buildings are generally based on punctual systems. Tests with smoke conditions simulation are also performed [25,30]. Mainly, speeds sensibly increase (about +15% when using continuous PLM on the floor in respect to punctual guidance light) along horizontal path, while the evacuation time decrease (up to about −65%) because people avoid wandering and more rapidly find the right direction [30]. The positive effect on speed is more effective when directional arrows are closely placed [30]. In staircase motion, despite high pedestrians densities, noticed speeds are higher than the predicted ones (up to about +15%) [34]. Finally, questionnaires qualitatively underlines that people assessed a good environment visibility perception of the system in relation to lighting (70% of people defined as "acceptable" or "good" the PLM scenario without emergency lighting) [34]. However, investigations on PLM application in historical buildings are skipped.

Following what is reported above, Italian-style historical theatres represent a good example of high fire risk historical buildings needed to be studied for decreasing their safety risk in respect to their architectural values. In fact, Italian-style theatres [37]:

- are portrayed as one of the most typologically common structures of our country, as they are a historic product of melodrama (a movement that was cradled and elected in Italy between 1700 and 1800);
- are characterized and fully covered by typical wooden structures of particular historic and artistic value (e.g.: the upper circle box and its slabs, the overhead scenery and the unusual roofing trusses);
- are open to the public;
- have a very particular architectural shape and spaces distribution;
- are often subject to massive and invasive modifications due to fire regulations.