Improving human safety in cultural heritage buildings: experiments on effectiveness of wayfinding systems in a theatre

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Highlights

This paper involves individuals’ safety in historical buildings in case of fire. An innovative continuous wayfinding system is proposed by using photoluminescent adhesive tiles placed on the paths floor. The system effectiveness is evaluated through evacuation drills in a significant case study (an Italian-style historical theatre). Evacuation times are reduced up to 30% while using the proposed system in respect to the traditional one, also because of the efficient addressing of secondary paths to occupants.

Abstract

Current fire safety regulations in historical buildings are generally limited to the number and dimension of exits and evacuation paths. This approach clearly clashes with preservation criteria because of the need of invasive layout modifications. On the contrary, a “behavioural design” approach could solve this conflict by proposing evacuation facilities based on effective human behaviours. This work proposes an innovative wayfinding system based on photoluminescent continuous signs. Experiments in a significant real world scenario demonstrate the possibility to considerably decrease the evacuation timing without building layout modifications.

Keywords

Building heritage fire safety, Historical theatres, PLM materials, Reversible systems for human safety and occupants’ evacuation, Continuous wayfinding system

1. INTRODUCTION

Building Heritage is characterized by high hazard and vulnerability levels in relation to the buildings features (building layout and materials, including wooden structures) and to the occupants (high density levels, people who can be often foreign with architectural spaces, people with motion disabilities) [1–3].

Italian-style historical theatres [4] 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, they: are portrayed as one of the most typologically common structures of our Country, as they are a historic product of 1700 and 1800 cultures; are characterized by typical wooden structures of particular historic and artistic value (i.e.: the upper circle box

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and its slabs, the overhead scenery, the roofing trusses); are open to the public; have a very particular architectural shape and spaces distribution; contains hazardous elements and activities (e.g.: inflammable materials in storage rooms; old wiring); are often subject to massive and invasive modifications due to fire regulations. In case of fire, the occupants’ evacuation is highly influenced by social features ("social attachment", information exchange [5]), interactions with smokes and related visibility/health problems [6], path choice depending on the familiarity with the building layout [7]. In particular, people generally move towards the known main entrance (because of memory effect [7]), while secondary exit paths are generally ignored, especially because of the low familiarity level with the structure and the inadequate characterization of signs. The same problems can be noticed in other historical buildings, because of the complex layout (with usual difficulties especially for Elderly), and contemporary use leading high occupants’ densities (such as for cultural activities, e.g.: museums, theatres, concert halls).

Related current fire safety regulations are mainly based on dimensional requirements (width, length) of evacuation paths and exits (e.g.: adding evacuation stairs; opening new exit doors; introducing fire-proof walls and doors) [2,8,9], but denote a schematic approach in relation to effective human behaviours at all [10]. Hence, these spaces are often unable to supply an adequate safety level to them, while the related needed building layout modifications highly interfere with the preservation and the minimal intervention criteria.

On the contrary, our research is aimed at increasing the evacuation safety levels for occupants by designing systems (both building components, architectural interventions, smart devices definition) that can help these occupants during the whole evacuation procedure, by taking advantages of a “behavioural” point of view. The related “behavioural design” (BD) activities are: understanding human behaviours and their needs during the emergency process, and then define behavioural models for representing evacuation interactions; designing systems (mainly, wayfinding systems) for interacting with them during the evacuation; testing the proposed solutions through experiments or behavioural models (and related simulation tools).

2. STATE OF ART

The BD, which is oriented to both fire scenario definition and human behaviours analysis to provide not-invasive solutions for occupants’ safety so as to preserve the architectural characteristics of the involved building, takes advantages of the Fire Safety Engineering (FSE) approach proposed by recent...
European fire safety guidelines [11] and the national regulations [12, 13]. FSE is essentially based on the estimation of the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET) [6, 11]. ASET depends on evaluations 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 spreading) and building features [6]. The RSET estimation is founded on human behaviours and interactions between man and the surrounding environment (i.e.: alarm systems; wayfinding signs; building layout) [10], during both pre-movement phase [14] and effective motion phase [15]. The egress of all occupants has to be performed in conditions of not-exceeded tenability criteria in the building itself (ASET>RSET) [11].

Previous works [16–18] demonstrate how the use of efficient wayfinding systems could significantly decrease the occupants’ egress time and so RSET, avoiding massive interventions on the building layout. These solutions can help people also in case of very low familiarity in respect to the architectural spaces or in particular environmental conditions (e.g.: darkness, smoke) [19]. Figure 1 resumes the main works about wayfinding system perception and influence: these researches are aimed at defining representation models and criteria for elements application in significant environment.

PLM wayfinding systems [22, 23] generally show high levels of effectiveness in lights on, blackout and smoke conditions [28]. Furthermore, they can be rapidly applied, do not need any electrical supply, are composed by not-invasive elements (by guaranteeing a “reversible” intervention), and ha slow level of maintenance. They can be distinguished between punctual systems (placed at paths intersections, plano-altimetric variations and over/ near the exit doors) and continuous systems (at least 1 directional sign per 5 m of path) [34]. Minimal features of this signage systems are defined by regulations and guidelines [22, 24]. They are really useful both along corridors and staircases because they could clearly outline the architectural spaces in low visibility conditions and in case of high density of evacuees along the path [35]. Different tests with high population sample and smoke conditions are performed [32, 33], but investigations on PLM application in historical buildings (and, in particular, in theatres) are skipped.

Hence, this work would like to fill this gap by starting from the BD point of view. A continuous PLM wayfinding system based on human attitudes in evacuation is firstly defined. Then, the application to the fire evacuation safety in a significant historical Italian-style theatre is used to providing an evaluation about these innovative concepts of emergency wayfinding elements.
3. METHODS

The work is divided in two phases. The first phase offers the definition of the innovative wayfinding system by taking advantages of the BD approach (the question is: “which are the individuals’ needs during an evacuation in respect to the wayfinding elements?”). The second phase involves the analysis of system effectiveness in a real world application by performing fire drills in a historical theatre. The system effectiveness is evaluated by comparing key performance indicators (evacuation times, speeds and selected paths) for the proposed system and the traditional ones (punctual wayfinding systems as summarized by Figure 2).

3.1. WAYFINDING SYSTEM DEFINITION

The proposed wayfinding system is based on the preservation of the historical building features (i.e.: minimal intervention criteria, reversibility criteria for the intervention) and on the behavioural needs in emergency evacuation, as also summarized by Figure 1.

The wayfinding system should have a low impact in terms of application and maintenance: for this reason, adhesive PLM signs are chosen. They are characterized by a minimum value of average luminance in in-situ application of about 500mcd/m2 after 2 minutes of blackout conditions and 300mcd/m2 after 10 minutes, according to ISO 16069:2004 (minimal value ≥20mcd/m2). From a behavioural point of view, previous works evidence how placing
continuous wayfinding system on the floor could increase the evacuation speed (and so reduce the evacuation timing) [37]. About the directional indicator, a chevron with a dimension of about 50mm is generally characterized by an identification distance of about 18m in emergency lighting conditions, for different age of the tested sample [20]. In addition, previous experiments [20] confirm the efficiency of a white arrow on a green background, also according to current regulations [24]. The PLM signs are able to help people in both lights-on and blackout conditions because of the supplied proper spatial description and the possibility to be seen also in smoke conditions [31,35], especially when they are applied on the floor and on the staircases (here, recommended positions involves at least the steps and the handrail). Additional variations in path sections and configurations (e.g.: doors, geometrical bottlenecks) should be evidenced by similar PLM elements (e.g.: PLM strips).

The traditional wayfinding facilities are generally based on Punctual Systems (PS), and could involve PLM materials. On the contrary, this work proposes a Continuous System (CS) for wayfinding based on the previous behavioural aspects, and by adopting adhesive PLM signs. Figure 2 summarizes the elements for the existing PS system and for the innovative CS one. All proposed and used signs are incompliance with current safety regulations [24,34,38].

3.2. EXPERIMENTAL TESTS

An historical Italian-style theatre, the “Gentile da Fabriano” theatre (Fabriano, Italy), is chosen for the experiments. This Italian-style theatre was design by Cleomene Luigi Petrini and Domenico Rossi and built between 1864 and 1884. It is a typical Italian horseshoe-shaped theatre with 721 seats on 4 tiers and a gallery, and it respects Italian regulations about fire safety [8].

In order to evaluate the systems effectiveness in case of significant occupants’ density and to also fill the current state-of-art gap on collective evacuation drill in historical buildings, the experiment involves 92 individuals from 18-80 years (about half of the sample is composed by females). The parterre and first tier are used for the drill, as shown by Figure 3: the PS is placed on the right side, while the CS is placed on the left side. Figure 3 also identifies the cameras positions that are used for recording the experiments. Individuals’ positions were randomly chosen by taking account a homogenous distribution for the two sides (by having similar positions in specular parts). The drill was performed with emergency lighting [39]. Before the experiments, lights are turned on for about 15 minutes in order to “recharge” the PLM signs (average illuminance in in-situ applications of about 40 lux).
Voluntary participants are invited in the theatre for a performance. For safety issues, the drill is announced, but starting time is not addressed. No previous information about evacuation paths is given to participants. Emergency lighting starts working, while the fire alarm rings and the voice alarm announces: “Please, the evacuation drill is started. The audience is invited to not hurry and to exit the theatre by following the wayfinding systems”. Each person is allowed to choose the evacuation path without changing the wayfinding system. The evacuation drill ended when the last occupant exited the theatre.

<table>
<thead>
<tr>
<th>Composing element: dimensions; description; positions; references</th>
<th>CS</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>directional PLM sign applied on the wall (height: 2m), placed at directional changes and over the exits; minimal dimensions: 200x200mm; arrow dimension: 35mm; green background CIE Yxy=(16.33, 0.25, 0.53); references: [24,38]</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Adhesive round PLM sign, applied on the floor (at the middle of the corridors); dimensions: diameter: 10cm; arrow: 50mm; distance between two consecutive elements: 70cm (7 signs for 5m); green background CIE Yxy=(16.33, 0.25, 0.53); references: [24]</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>PLM strip applied on the staircase steps (in order to evidence the steps itself); dimensions: 2,5x60cm</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>PLM strip applied on evacuation handle (in order to evidence the exit); dimensions: 2,5x60cm</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 2. Elements composing the tested wayfinding systems: description; figures; presence in the CS and in the PS.
Evacuation speeds, time and path choices are collected in order to compare PS and CS effectiveness. Data are retrieved by analysis videotapes from applied fixed cameras. In addition, at the end of the drill, individuals are asked to fill out a questionnaire about their own evacuation wayfinding system liking (“Did you find the system helpful in evacuation choices?”).

4. RISULTATI

Figure 4 shows, from qualitative and quantitative point of views, how the CS increases the safety level for the building occupants during the evacuation. In fact, evacuation times are reduced up to 27%, as a counterweight to average evacuation speed increasing (up to 30%). The pre-movement phase [14] seems to not influence the evacuation timing for the two systems, because the 90% of population starts its evacuation at the voice alarm. CS effectively supplies a clear information to evacuees, as shown by Figure 4 high percentage of people who appreciate the system (according to questionnaires answers). The CS high effectiveness is mainly due to the possibility of the description of architectural spaces also in low visibility conditions. Figure 5 shows how, avessero avuto problemi di visibilità ed identificazione delle informazioni da esso fornite.

4. RISULTATI

La Figura 4 dimostra come da un punto di vista quantitativo e qualitativo il sistema continuo proposto (SC) riesca effettivamente ad incrementare il livello di sicurezza delle persone in evacuazione. Inoltre si ottiene una riduzione significativa (fino al 27%) del tempo di evacuazione, corrispondente ad un aumento della velocità di esodo. Il tempo di pre-movimento [14] non ha inciso sulle differenze di tempo totale registrate tra i due sistemi, in quanto il 90% circa del campione ha comunque iniziato l’evacuazione all’annuncio vocale di evacuazione. Il sistema SC riesce effettivamente a dare un’informazione chiara alle persone sulla direzione da seguire, come sottolineato dall’alto livello di gradimento degli stessi: fattore cardine è da un lato la fotoluminescenza degli elementi, che in condizioni di illuminamento ridotto ha aumentato la possibilità di comprendere le informazioni, e dall’altro l’avere un percorso chiaramente marcato in maniera continua. La Figura 5 mostra come SC riesca inoltre a far individuare agevolmente alla persone le vie di fuga secondarie: il 90% delle persone che hanno utilizzato il SP partendo dalla platea hanno deciso di utilizzare l’uscita centrale.
while using the CS, people easily move towards secondary paths. In particular, at the parterre, the 90% of occupants in PS conditions move towards the main entrance, because of significant memory effect influence. These people are asked to explain the reason of this choice: the 33% of the sample uses this path because of the familiarity to this path (memory effect) or the presence of many people moving along it (herding behaviours) [40]. On the contrary, more than the 30% of sample for CS choose the lateral parterre door. In this way, overcrowding phenomena along the main path (the one of the main entrance) are sensibly reduced and evacuation times could be significantly reduced.

<table>
<thead>
<tr>
<th>Quantities in motion</th>
<th>PS</th>
<th>CS</th>
<th>ΔT(%)</th>
<th>ΔV(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T – evacuation time (s)</td>
<td>91</td>
<td>68</td>
<td>-25.2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>167</td>
<td>122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V – evacuation speeds (m/s)</td>
<td>0.28</td>
<td>0.37</td>
<td></td>
<td>+30.4%</td>
</tr>
<tr>
<td></td>
<td>0.47</td>
<td>0.60</td>
<td></td>
<td>+31.6%</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Questionnaires answers</th>
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<tbody>
<tr>
<td>Signs system were:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Useful during the evacuation</td>
<td>34%</td>
<td>87%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hard to be seen and understood</td>
<td>33%</td>
<td>5%</td>
<td></td>
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</tbody>
</table>

Figure 4. Differences between quantitative and qualitative results for the PS and the CS.

Figure 5. Tracing the evacuation paths for the parterre.
5. CONCLUSIONS

Fire risk in the historical building is a very important issue because of intrinsic vulnerability aspects, the complex architectural layout, and the presence of many people (who are not familiar with the space itself). The impact of a fire would be able to provoke very large damages not only to the heritage but also to the occupants. Current regulations propose massive interventions on the building configuration in order to increase individuals’ safety level. On the contrary, this goal could be easily gained by applying innovative wayfinding systems that are perceived and used by people in a correct and efficient way. This study proposes a robust innovative wayfinding system by taking advantages of a “behavioural design” approach: understanding individuals’ needs; developing solution to accomplish their requests; testing the solutions by validations activities; defining rules for describing human interactions with the proposed solution, so as to also develop models for their simulation. The proposed system is based on continuous PLM signs, which: could give an efficient support to evacuating pedestrians also in low visibility conditions (black-out, smoke presence); could offer a good description of the architectural spaces to occupants also in low visibility conditions; is also easy-to-apply and remove because composed by adhesive elements and no supplies are needed. An Italian-style historical theatre is chosen as a representative case study within historical buildings in order to verify the proposed system effectiveness in respect to current punctual exit signs. This kind of buildings has significant problems in case of evacuation because of the high occupants’ densities, the large presence on the national territory and the current use of these buildings. Results show how evacuation times significantly decrease in collective drills (up to -27%) while occupants are guided by the proposed system. Advantages are essentially due to the clear path and spaces identification given by the short distances between two consecutive signs. Hence, this study generally suggests that wayfinding systems on existing buildings should involves a smaller distance between signs in both corridors and stairs, and the correct marking of all plan layout variations (path direction variations, stair-steps). CS can be easily introduced in historical Italian-style theatre in order to decrease the total evacuation time. According to the innovative performance-based fire safety engineering, this means an increasing of the occupants’ safety level. The absence of supply and physical modifications of the building allows to effectively preserve architectural and cultural heritage features. Future researches should enlarge the sample dimension of similar innovative systems in historical buildings, by also including other buildings typologies per la presenza di persone all’interno di uno spazio spesso complesso e non perfettamente conosciuto. Se un incendio si presentasse in un edificio storico, i danni sarebbero ingenti sia per il patrimonio artistico e culturale sia per gli occupanti. La normativa adotta misure di sicurezza invasive per garantire alle persone di poter abbandonare il luogo in sicurezza: questo implica la messa in discussione dei caratteri specifici dell’organismo edilizio che un’alta densità di occupanti e la sua corretta conservazione. Al contrario, gli strumenti del behavioral design riescono a offrire soluzioni a basso impatto, reversibili, e soprattutto efficienti per la sicurezza delle persone. Il presente studio si è occupato della formazione di un sistema di evacuazione progettato sulla base dei requisiti comportamentali e non invece ispirato alla logica deterministica secondo cui è l’elemento il suo spazio a produrre un effetto d’uso (anche sociale) sull’individuo. Il sistema è di tipo fotoluminescente per essere visibile anche in condizioni di bassa visibilità ed illuminamento ambientale critico, e prevede per dare un’informazione costante lungo il tragitto; esso inoltre è facilmente rimovibile e non richiede assistenze murarie o elettriche. Come caso di studio, si è scelto quello significativo di un teatro storico all’italiana, poiché tale tipologia di edificio storico, molto diffuso sul territorio nazionale, vede implicito sia un potenziale rischio incendio elevato che un alta densità di occupanti esposti. Sebbene le persone non siano avverse al sistema proposto, non essendo questo applicato normalmente negli edifici, la prova collettiva di evacuazione ha dimostrato un miglioramento della velocità fino al 30% rispetto ai normali sistemi di wayfinding punituali. A controprova, il livello di gradimento secondo questionario ai partecipanti è stato elevato. Pertanto, visti i canoni di compatibilità con l’intervento reversibile sulla struttura e l’ausilio fornito in evacuazione, si ritiene che il sistema possa essere proposto per incrementare il livello di sicurezza negli edifici storici. Naturalmente ulteriori prove potranno in futuro fornire prove di efficacia del sistema su grande scala. Il presente studio dimostra inoltre che il sistema proposto può convenire alle necessità e ai comportamenti umani, e riesce quindi a sfruttare i benefici della risposta degli individui. L’importanza di comprendere e codificare il comportamento umano effettivo in situazioni ambientali di stress (come può essere quella dell’emergenza evacuazione) è cruciale quindi per una corretta progettazione dello spazio. Nel campo afrontato, si invita a future ricerche sulla percezione dei segnali di evacuazione e sui criteri di scelta dei percorsi di esodo, attraverso prove reali tradizionali, test in realtà virtuale, esperimenti individuali con strumenti di monitoraggio dell’attività umana innovativi e oggettivi (come i sistemi EEG), analisi di casi reali. Infine, il livello successivo dovrà necessariamente integrare le analisi
and uses (e.g.: museums, hospitals). Furthermore, some investigations should focus on the optimization of the systems (in terms of signs position, and number minimization), by taking advantages of deeper experimental activities about human behaviours and perception of the wayfinding elements. To this purpose, innovative techniques that directly measure typical individual quantities to these tasks (e.g.: brain activities, pupils motion) should be involved. Finally, a higher level of aesthetic design and architectural integration of sign should be reached, for mainly reducing the “visual” impact of wayfinding systems in normal conditions use. The definition of low-impact wayfinding technologies could jointly involve the integration between signs systems and sensors-based technologies (both about occupants’ behaviours and building response to fire).

6. REFERENCES


[17] Vilar E. [et al.], Effects of competing environmental variables and signage on route-choices


