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AAP-3937; No. of Pages 12

ARTICLE IN PRESS

Accident Analysis and Prevention xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Empirical investigation on safety constraints of merging pedestrian crowd through macroscopic and microscopic analysis

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ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form 6 October 2015
Accepted 10 October 2015
Available online xxx

Keywords:
Crowd dynamics
Crowd safety
Disaster management
Merging angle
Blocked vision
Evacuation

ABSTRACT

A recent crowd stampede during a New Year's Eve celebration in Shanghai, China resulted in 36 fatalities and over 49 serious injuries. Many of such tragic crowd accidents around the world resulted from complex multi-direction crowd movement such as merging behavior. Although there are a few studies on merging crowd behavior, none of them have conducted a systematic analysis considering the impact of both merging angle and flow direction towards the safety of pedestrian crowd movement. In this study, a series of controlled laboratory experiments were conducted to examine the safety constraints of merging pedestrian crowd movements considering merging angle (60°, 90° and 180°) and flow direction under slow running and blocked vision condition. Then, macroscopic and microscopic properties of crowd dynamics are obtained and visualized through the analysis of pedestrian crowd trajectory data derived from video footage. It was found that merging angle had a significant influence on the fluctuations of pedestrian flows, which is important in a critical situation such as emergency evacuation. As the merging angle increased, mean velocity and mean flow at the measuring region in the exit corridors decreased, while mean density increased. A similar trend was observed for the number of weaving and overtaking conflicts, which resulted in the increase of mean headway. Further, flow direction had a significant impact on the outflow of the individuals while blocked vision had an influence on pedestrian crowd interactions and merging process. Finally, this paper discusses safety assessments on crowd merging behaviors along with some recommendations for future research. Findings from this study can assist in the development and validation of pedestrian crowd simulation models as well as organization and control of crowd events.

1. Background

Pedestrian crowd safety has emerged as an increasingly important research topic among emergency response planners or managers, transport engineers, architects, fire and safety engineers, and police authorities. There have been numerous crowd accidents in both developed and developing countries where dense crowds and panic have led to stampedes resulting in fatalities and injuries, and these numbers have been growing rapidly in the past decade (Still, 2015). As one of the most populous countries in the world, China is facing huge challenges in terms of efficient and safe crowd management on major public infrastructure. In fact, in the past five years, crowd disasters have resulted in nearly 100 fatalities and over 200 serious injuries in China (Still, 2015). Most of these accidents resulted from complex crowd movement behavior e.g. turning, crossing and merging. Such complex multi-direction crowd behaviors are likely to create bottleneck impeding the outflow of the pedestrians. Documented studies on crowd accidents have highlighted that stampedes are more likely to occur at those bottleneck points (Chertkoff and Kushigian, 1999; Lee and Hughes, 2005, 2006; Helbing and Mukerji, 2012). Thus, it is essential to gain a thorough knowledge on mechanisms of crowd movement patterns at specific bottleneck sections as any external perturbations in a high density complex movement can create shockwave and stop–go condition resulting in negative consequences such as stampedes (Helbing et al., 2005, 2007).

One of the most frequently observed complex crowd dynamics phenomena is the merging behavior as crowd movements from

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http://dx.doi.org/10.1016/j.aap.2015.10.009
0001-4575/

Please cite this article in press as: Shi, X., et al., Empirical investigation on safety constraints of merging pedestrian crowd through macroscopic and microscopic analysis. Accid. Anal. Prev. (2015), http://dx.doi.org/10.1016/j.aap.2015.10.009

multi directions join to form a single streamline (Roess et al., 2005). However, limited empirical data exist in the literature on merging crowd behavior (Shiwakoti et al., 2015), despite the fact that merging architectural configurations have been identified as a potential bottleneck in the previous researches on crowd disasters (Chertkoff and Kushigian, 1999).

The empirical studies that looked into merging crowd behavior are Zhang et al. (2011) and Shiwakoti et al. (2015). However, Zhang et al. (2011) only studied a single right angle merging setup (also referred as T-junction) through a macroscopic approach. They did not study the impact of different merging angle on the crowd flow neither the impact of flow direction. Shiwakoti et al. (2015) focused on the microscopic approach of understanding the impact of different merging angle on the speed reduction. However, a thorough understanding of both microscopic and macroscopic parameters of particular crowd behavior is crucial in the development and validation of any crowd simulation model (Shiwakoti et al., 2008; Duives et al., 2013). Macroscopic properties of crowd movement behavior (i.e. density, flow, velocity and their inter-relations) are important elements in developing flow-based models that utilized carrying capacity to predict the crowd dynamics, and these models are often employed to plan escape route or optimize crowd flow. However, such models can only provide an insight on some phenomena such as congestion formation and jam transition, but it is difficult to provide the clear evidence and reason behind those phenomena. Through analysis of microscopic properties such as headway, instantaneous speed and their distributions, we can have an insight on the possible causes for those crowd phenomena. Particularly, microscopic approach can take into account the local interactions to capture additional delays which are important during emergency situations. These local interactions finally lead to the global outcome or collective behavior which can be best studied with macroscopic properties. A reliable crowd simulation model should be able to reproduce these micro–macro properties and hence a systematic empirical analysis of merging crowd behavior is of paramount importance to develop and verify a simulation model intended to replicate merging behavior.

To our knowledge, there is no systematic microscopic and macroscopic empirical study that has looked into the impact of different merging angle and flow direction on the outflow and safety of pedestrian crowd, which we intend to achieve in this paper.

The paper is structured as follows: the next section discusses the relevant literature on merging crowd behavior and research gaps. Then, controlled laboratory experimental studies with merging pedestrian crowds are presented. This is followed by the analysis of detailed results from the experiments considering macroscopic and microscopic perspectives. The final section presents the discussion and conclusion.

2. Literature review

Pedestrian crowd dynamics have been studied from two perspectives i.e. mathematical simulation modeling and empirical studies (Shiwakoti et al., 2008; Shiwakoti and Sarvi, 2013a). Research and modeling of pedestrian behavior date back over four decades (Henderson, 1971; Fruin, 1971). Similar to vehicular traffic modeling, crowd dynamics simulation models have been developed mainly from macroscopic and microscopic approaches (Shiwakoti et al., 2008; Duives et al., 2013). Most of these models for complex crowd movement have been inspected, verified and validated visually based on computer graphics rather than with complementary empirical data (Shiwakoti et al., 2008). This may have a bearing effect on the reliability of model's prediction. It is not the focus of the present study to review these mathematical simulation models (interested reader can refer to Shiwakoti et al., 2008; Duives et al., 2013, for the detailed review), but rather to examine the underlying empirical foundations on merging crowd behavior and its safety implications. Previous studies have identified that there is a lack of empirical data towards understanding the complex crowd movements including merging crowd behavior (Kalakou and Moura, 2014; Shi et al., 2015; Shiwakoti et al., 2015).

In terms of simulation models for merging behavior, there have been a few studies that focused on the interactions of pedestrian crowd at the merging section. For example, merging interactions have been simulated at the floor–stair interfaces (Galea et al., 2008; Hamacher et al., 2011; Ding et al., 2013) or at the standard T-junction (Tajima and Nagatani, 2002; Peng and Chou, 2011; Berrou et al., 2007; Craesmeyer and Schadschneider, 2014). All these simulation studies highlighted that merging section can potentially create a bottleneck resulting in congestion and clogging. Although these findings are important step towards understanding the merging crowd behavior, these models currently lack the validation with empirical data especially regarding the effect of merging angle and flow direction.

With regards to empirical studies, Zhang et al. (2011) organized a series of controlled laboratory experiments with 350 German participants at a T-junction. Through a macroscopic data analysis, they found that the fundamental diagrams are not comparable between different pedestrian walking facilities. Congestion was also observed at the merging section. In another study, Takeichi et al. (2006) and Yang et al. (2012) looked at stairway–floor merging cases, and through macroscopic approach, they noted the congestion forming at the merging section. Given the lack of complementary data on extreme emergency situations, Shiwakoti et al. (2014) and Dias et al. (2013) performed experiments with panicking ants to investigate the turning, intersecting and merging configurations on the collective egress and found that merging configurations create negative effects on the flow of non-human organisms as well.

Recently, Shiwakoti et al. (2015) conducted experiments with 22 college student participants to study the impact of merging angle on the outflow of a pedestrian crowd from a microscopic perspective. It was found that as the merging angle increased, there was a reduction in instantaneous speed in the merging area, which resulted in the reduced outflow of the pedestrians. However, Shiwakoti et al. (2015) focused only on the impact of merging angle and desired speed category through microscopic analysis. This study considers the impact of both merging angle and flow direction via systematic macroscopic and microscopic analysis. We have found in our study that along with merging angle, flow direction also has safety implications for a pedestrian crowd. For the first time, our empirical study has shown that the inverse right angle merging is significantly inefficient in terms of outflow and density transition as compared to the normal merging right angle or other merging angle due to the difference in the direction of merging behavior. It is crucial to understand the underlying mechanisms of both merging angle and flow direction as previously inverse right angle merging behavior has led to the love parade disaster in Germany in 2010 where 21 people were killed and more than 500 people were seriously injured (Helbing and Mukerji, 2012). Also recently a stampede occurred near such junction in 2015 Hajj pilgrimage in Mina, Mecca resulted more than 1100 fatalities and over 900 injuries (The Times of Israel, 2015) which again demonstrate the need to understand such standard and inverse merging T-junction.

In addition, the experimental layout and procedure in the present study are more advanced and realistic than Shiwakoti et al. (2015). We have a greater number of participants (70 vs. 22) along with the blocked vision condition, as expected in real-world merging architectural configurations. For example, in Shiwakoti et al. (2015), boundary materials consisted of ropes and chairs (allowing participants to see each other) rather than the solid boundary walls

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