ANALYSIS OF EVACUATION PERFORMANCE OF MERGING POINTS IN STADIUMS BASED ON CROWD SIMULATION

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ABSTRACT
Holding huge amount of spectators simultaneously during sports and recreational events, the problem of outdoor stadiums is increasingly focusing on how to improve evacuation performance. At first, the prescriptive codes related to stadium evacuation were compared, and the characteristics and movements of stadium crowd were studied to build more reliable evacuation simulation scenarios. Next, the design variations of most congested merging points in outdoor stadiums, which involve gangway intersections, vomitory access and stairway access underneath the stands were investigated. Finally, we used a CA model to simulate the evacuation processes in different cases. By analyzing the output value of egress time, waiting time and total cost through the journey, evacuation performances of different design strategies were compared and discussed.

INTRODUCTION
Stadium is one of the most populated assembly occupancies for crowd gathering and public events. In the last hundred years, stadium disasters were mostly crowd related and resulted in heavy casualties (Warne 1999). Those tragic events promoted disaster reports and standards update (Taylor 1990, FIFA Guidelines 2008, Green Guide 2008); related research on crowd behaviour, management and control (Mann 1989, Sime 1995, Tubbs 2007); crowd movement, dynamics and evacuation studies under both normal and emergency situations (Pauls 1984, 2010, Graat et al. 1999, Still 2000, Hoskin 2004, Johnson 2010). One important way of ensuring crowd safety is to design circulation system that has higher evacuation performance. Egress design in stadiums is mainly about determining total width of exits based on the minimum requirements of evacuation time and recommended flow rate in building codes (Sheard et al. 2007). However, evacuation performance of different configurations in merging flow areas received very little attention. Meanwhile, experimental studies on merging behaviours are mostly focus on stairway access in multi-level or tall buildings in general (Tomonori et al. 2005, Galea et al. 2008, Boyce et al. 2009), not specific to the building type and circulation design. For many large stadiums in which egress designs are beyond the limit of prescriptive codes, simulation gradually became a practical way in evaluating the evacuation performance and optimizing design strategies since the release of some computer models (Thompson & Marchant 1995, Owen, Galea and Lawrence 1996, Still 2000, Klüpfel 2003) in the mid-1990s. Especially for the investigation of evacuation performance of spatial variables such as parameters and layouts of egress routes layout in the context of a complex environment, crowd simulation seems to be the only way to solve the problem.

In this paper, we used simulation experiments to compare and analyze the evacuation performance of different egress routes parameters and layouts of three merging points in a typical subsection of spectator areas. The safety index, crowd behaviours and movements in stadiums were studied. Individual and crowd profile on spectators were investigated based on the statistical data of consumer behaviour studies. The simulated spaces were supposed to be a subsection of spectator areas with the same stand dimension, total width of exits and spectator capacity, but different route configurations or outflow-inflow differences at gangway intersections, vomitory access and stairways underneath the stands. The software STEPS (MacDonald 2003) was selected as the simulator. A total number of 60 scenarios were considered in this software, in which the settings of spectators and their movement capabilities were identical, but egress routes design were different at three merging points. The simulated results demonstrated flow confluence along egress routes had certain impact on crowd evacuation in stadiums.

BACKGROUND STUDIES

Safety index of stadium evacuation
Evacuation time in terms of minutes is perhaps the most important performance-based index for evaluating the effectiveness of stadium evacuation. The maximum allowable evacuation time value in building codes is a reference for architects to calculate the total width of the exits during schematic
Crowd characteristics and movements

The characteristics of stadium crowd vary according to the types of holding events, such as football match and concert. Widely different crowd behaviour may be experienced in stadiums. (Carey et al. 1993). Stadium or entertainment type of crowd has a much higher chance of occurring destructive behaviour than other crowd populations (Berlonghi 1993). In terms of typology, stadium crowds during sports events can be described as follows:

- Attending the events as the primary purpose
- Moderate duration of time
- Certain timing of start and finish
- Individualized seating allocations
- High level of conflicts and interaction potentiality
- Members include singles, partners and groups of friends or business
- Negligible luggage

Group demographic heterogeneity of stadium crowd seems moderate for their common primary purpose. The unique composition of stadium crowd can be described as follows (Warne 1999):

- Young/Elderly
- The disabled, ill and injured people
- Victims of accident or assault
- Lost persons
- Drunks
- Partisans and neutrals

In addition, the tendency to diminish individual characteristics in favour of a collective personality makes stadium crowd more powerful and harder to control. The cultural background and style of club are factors have potential influence on the ‘group personality’ of stadium crowd. An egressing stadium crowd is unlike most other moving crowds (Berlonghi 1995). The majority of crowd attempts to leave as quickly as possible after the events. It was observed that behavioural factors play a significant role in such disparity (Hoskins 2004):

- Lack of visual stimulus
- Lack of choice
- Acceptance of a collective identity

Crowd movement is affected by human factors such as individual locomotion capability, dynamic decision-making abilities, crowd density and complex behaviours, as well as environmental factors such as the physical condition of egress routes and their recognisability. Studies show that excess egress time and waiting time would promote level of anxiety, thus change the egress crowd into escape crowd with a tendency of violence.

CASE STUDIES BY CROWD SIMULATION

Different circulation design strategies at three congested merging points in stadiums were compared in terms of evacuation performance by crowd simulation. The settings of attributes of persons inside stadiums were investigated. The same settings for occupants were used and the occupants were places exactly on their seats for each simulation. In

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>STAIRS</th>
<th>LEVEL</th>
<th>SUBJECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predtechenski i (1969)</td>
<td>0.66</td>
<td>0.8</td>
<td>Stadia max flow rate</td>
</tr>
<tr>
<td>Poyner et al. (1972)</td>
<td>–</td>
<td>1.42</td>
<td>Soccer stadium</td>
</tr>
<tr>
<td>Neufert (1980)</td>
<td>1.25</td>
<td>–</td>
<td>Olympic Stadium Amsterdam</td>
</tr>
<tr>
<td>Taylor Report (1990)</td>
<td>–</td>
<td>1.67</td>
<td>Video footage of Gate C from Hillsborough disaster</td>
</tr>
<tr>
<td>Templer (1992)</td>
<td>1.03</td>
<td>1.26-1.42</td>
<td>Commuters + stadium (Fruin 1970)</td>
</tr>
<tr>
<td>Green Guide (1990)</td>
<td>1.21</td>
<td>1.82</td>
<td>Unknown (for purpose of calculation only)</td>
</tr>
<tr>
<td>Gwynne (2009)</td>
<td>–</td>
<td>0.77</td>
<td>Observed specific flow rate-width</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rate-eff. width from the arena exits</td>
</tr>
</tbody>
</table>
this way, the effects of changing local configurations can be studied. Building models were series of egress routes design variations based on a baseline model with fixed dimension and total width of exits. For each environmental change, two simulations were carried out by inputting possible different people groups.

Settings of attributes

The population of occupants depends on seating capacity in stadiums. The most unfavourable condition is that all seats are filled up. In this study, the section of spectator area has an occupant load of 2,800. The population are refer to the sitting spectators only, over populated and standing possibilities are not included. In addition, the simulated crowd means spectators, rather than management stuff, athletes, news reporters and technical officials.

(1) Individual types: Four types of individuals were considered in simulations to represent occupant diversity and different movement capabilities. Table 2 shows detailed information on the attributes (such as age, gender, walking speed and patience level) of each individual assigned in this study. The patience level of seniors and teenagers was given slightly lower than adults based on Becker-Mulligan model, in which age has U-shape relationship with level of patience (Becker and Mulligan 1994, 1997). Pedestrian walking speeds on stairs and level surfaces were based on the Fruin’s work (Fruin 1971). Body size was set up according to the average of literature (Fruin 1971, Still 2000, Thompson 2003, Human dimensions of Chinese adults, 1988), which served more for identification rather than physical function.

Table 2
Settings of spectator types and related parameters in the seating area

<table>
<thead>
<tr>
<th>INDIVIDUAL TYPE</th>
<th>PATIENCE</th>
<th>SPEED 1</th>
<th>SPEED 2</th>
<th>BODY SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>0.6</td>
<td>1.3</td>
<td>1.0</td>
<td>0.5×0.3×1.7</td>
</tr>
<tr>
<td>Female</td>
<td>0.6</td>
<td>1.1</td>
<td>0.7</td>
<td>0.4×0.3×1.6</td>
</tr>
<tr>
<td>Senior</td>
<td>0.4</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4×0.2×1.6</td>
</tr>
<tr>
<td>Teenager</td>
<td>0.4</td>
<td>0.9</td>
<td>0.6</td>
<td>0.3×0.2×1.3</td>
</tr>
</tbody>
</table>

Notes: Speed 1: Speed on level surfaces (m/s)
Speed 2: Speed on stepped surfaces (m/s)
Body size: shoulder width × back thickness × height (m)

(2) Crowd demography: The occupant crowd was composed of above four types of individuals. The composition of crowds would largely depend on the type of holding events. Stadiums were mainly used for major sporting, cultural or entertainment events, in which the audience profiles such as age and gender distribution varied widely. Table 3 shows mix ratios of above four types of individuals in sports and cultural crowds. The manning scales are the average of the statistical data of consumer behaviour studies on the Chinese football club in Beijing (2003, 2004), National A League Football Match in Changsha (2005) and Australia multi-cultural events (2008, 2010).

Table 3
Settings of crowd demography in the seating area

<table>
<thead>
<tr>
<th>CROWD TYPE</th>
<th>MALE</th>
<th>FEMALE</th>
<th>SENIOR</th>
<th>TEENAGER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sports crowds</td>
<td>60.7</td>
<td>13.4</td>
<td>6.7</td>
<td>19.2</td>
</tr>
<tr>
<td>Cultural crowds</td>
<td>30.2</td>
<td>32.8</td>
<td>23</td>
<td>14</td>
</tr>
</tbody>
</table>

Description of spaces

A section of typical spectator area in stadiums was selected as baseline model for this study. The seating capacity is about 2,800 spectators. The total width of vomitories and system exits are 6.6m, which allows 12 pedestrians walking through parallel. The selected terraced stand is of length 42m, width 32m, which contains continuous 40 rows with each row width 0.8m. All of the radial gangways are 1.2m wide, which allows two adults standing and walking side by side.

Figure 1 12 gangway and vomitory layouts planes for a subsection of terraced stand in stadiums

(1) Gangway intersections: Twelve types of gangways and vomitories arrangements have been developed. Figure 1 shows the design variations of terraced stand in planes, in which B-series models have the same radial gangway and exits arrangements with A-series models, but increased a 1.6 wide lateral gangway in the middle. For achieving unobstructed
sightlines on the upper stand of B-series models, the first rows of upper stands were elevated 0.8m vertically, and additional lateral stairs of width 0.8m were set up on the lateral gangway, which leaves the clear width 0.8m on the most restricted area of the lateral gangway. Each vomitory width was 3.3m for Model 1-4, which allowed six pedestrians walk in parallel, and 1.65m (allows three pedestrians parallel walking) for Model 5 & 6, in which 4 vomitories were provided in each model.

(2) Vomitory access: As the exit of terraced stands, vomitory was usually considered as the most restricted point along egress routes in stadiums during evacuation calculations. Model B3 & B4 in Figure 1 were selected as the baseline models for the study of vomitory access. In these models, the radial gangways are $2 \times 1.2$m on both upper and lower stands. Only the locations of radial gangways on the lower stands are different: the walking direction of B3 is the lateral gangway, while B4 towards the vomitory. On this basis 12 kinds of situations regarding the pedestrian outflow – inflow stream differences were developed and compared to verify the changes of evacuation performance. Figure 2 shows the relative position, number of pedestrian streams (550mm wide for each stream) and the inflow – outflow stream differences at vomitories access.

(3) Stand underneath: Stairway access underneath the stands is one of the most congested areas in stadiums evacuations. The walking directions of seating areas and locations of system exits determine vertical evacuation measures on the terraced stands, thereby further influence vertical pedestrian confluence underneath the stands. There are three types of basic vertical circulation measures in relation to walking directions: upward (Model 1 & 2), downward (Model 3 & 4) and walking towards the inter floor (Model 5 & 6). Figure 3 shows these three vertical circulation measures in sections with system exits on the ground floor and first floor separately.

Three merging points introduced above would be the most congested areas in stadium evacuations from observation. Local congested crowd could block circulation within a range nearby, result in much longer waiting time and delay. Therefore, it is worthwhile to develop simulation models accordingly and compare the evacuation performance in different models in terms of egress time, waiting time and total cost of the journey.

The scenarios

We did numerical experiments for above three locations with sixty scenarios (Figure 4-6):
• Scenario 1-24: Twelve gangway and vomitory arrangements as shown in Figure 1 were examined in STEPS. Figure 4 shows locations of remaining spectators in different models after evacuation started three and a half minutes.

• Scenario 25-48: Twelve vomitory access arrangements with different outflow – inflow stream differences (Figure 2) in baseline Model B3 & B4 were examined. Figure 5 shows the crowds condition of vomitories access after evacuation started three and a half minutes.

• Scenario 49-60: Six vertical circulation measures with different walking directions on the terraced stands (Figure 3) were examined. Figure 7 shows locations of spectators in different models by sections after evacuation started three minutes. The total width of system exits for all 6 models were 6.6 meters, which equalled to the total width of their vomitories.

Figure 4. Locations of remaining spectators after evacuation start 3.5 minutes on the terraced stands

Figure 6. Locations of remaining spectators after evacuation starts 3 minutes
Simulated results

(1) Increased lateral gangway: Lateral gangways are usually adopted on the seating areas of large stadiums to improve evacuation performances. The increased lateral gangway links radial gangways on upper and lower stands, and allows spectators to have vomitory option conveniently before they leave the terraced stands. However, it also brings visible confluences at the gangway intersections, and lowers the seating capacity. Figure 7 and Figure 8 shows the simulation results of 12 models shown in Figure 1. With extra lateral gangway (Model B) of 1.6m (0.8m on the most restricted positions) clear width: 1) increased the total egress time to 327s from 310s on average of six models, which is 5.5% higher than the base-case; 2) increased total waiting time through the model to 3834s from 3320s on average, which is 15.5% higher than the base-case.

(2) Increased inflow stream: In the area of vomitory access, pedestrian flow comes directly from two or three directions: two of which perpendicular to the vomitory and one in consistence with it. In the context of vomitories (3.3m*2) serve as system exits, with fixed width and location, as well as direct inflow directions and locations, the possible spatial problems becomes pedestrian outflow-inflow stream differences. Figure 9-12 shows the simulated results of 12 models in Figure 2. Increased pedestrian inflow stream at vomitories access in models B3 and B4: 1) decreased egress time slightly in the first four models, while increased dramatically in the last two of B4 models. However, in B3 models the results were just the reverse; 2) influenced total cost through the journey in B3 much greater than B4 models, in which the average total cost was 17.9% higher (from 13.18s to 15.54s); 3) increased outflow waiting time sharply in both B3 and B4 models to 44.73s from 23.18s, which was 93% longer on average. In 6 models, average waiting time in model B4 is 37.3s, slightly longer than 36s in B3, which is 3.6% higher; 4) changed inflow waiting time to some extent in the first 4 models of both B3 and B4, but greatly on the last two. Average inflow waiting time in model B3 is much longer than B4, which is 3.6 times increase from 16.5s to 60s.
(3) Increased vertical merging flow: Figure 13 & Figure 14 show the egress time and waiting time of 6 models (Figure 3) with different vertical circulation measures 1) The average egress time of two downward evacuation models is 294s, which is considerably shorter than upward evacuation of 306.5s and walking towards the inter floor of 305s. 2) Exits locate on the first floor increased total egress time to 306s of three models on average, from 300s on the average of two models, which is 2.2% increase than the base-case. 3) The average waiting time of downward evacuation models (184.6s) were about twice longer than walking towards the inter floor (93.5s), which is almost twice longer than upward evacuation models (54.1s) as well. 4) Exits on the first floor increased waiting time at exits to 177.3s from 44.1s in three models on average, which is 4 times longer than base-line case.

CONCLUSION

This paper presents case studies of evacuation simulation supporting stadium egress design and safety evaluation. Three merging points with 30 possible layouts or parameters in stadium circulation system were studied numerically using the software STEPS. Spectator individual and crowd profiles were set up based on statistical data in consumer behaviour studies. Design alternatives were selected by investigating numbers of stadium projects. The simulated results show that for a given total width of system exits, evacuation performances varied greatly in models with different egress routes design. Output data indicate that egress time increased along with the increasing lateral gangway, adopting upward evacuation measure, and locating exits on the ground floor. Waiting time at exits increased dramatically by locating system exits on the first floor and increasing inflow stream on the merging points at vomitories.

Evacuation performance of all the above-mentioned configurations were compared. 1) In 12 models of spectator stands, egress time of Model A2 & A4 is
the shortest (291s), which is 8.6% lower than average. Moreover, waiting time of Model A4 is shortest (2753s), 23% shorter than average; 2) Among 12 models with different vomitory configurations and/or parameters regarding outflow-inflow differences, B3(-8) has the shortest egress time and lowest total cost, but it is not recommended in project design due to its oversized passage area and increased viewing angle on the upperstand. In the remaining models, B3(4) has a good overall performance: lower inflow and outflow waiting time, and acceptable egress time and waiting time. 3) In 6 vertical circulation models, Model 6 shows shortest egress time (295s), and considerably short waiting time at exit (54.76s), which is 49.5% shorter than average.

The findings of these experiments show that further research is needed to develop comprehensive guidelines for safety assessment which include more quantitative evaluation values in performance-based regulations. For assembly occupancies like stadiums with large amount of spectators and complex circulation systems, long time waiting during evacuation process may raise the motion of anxiety and agitation, thus evoke non-adaptive behaviours within the crowds. Therefore, waiting time of main elements and cost factors should be considered in evacuation evaluations, in which waiting time of main elements and merging points on egress routes should be assessed and held within limits.

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