Front-to-back communication in a microscopic crowd model

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Summary. Failures in front-to-back communication (F2BC) in crowd disasters are commonly cited, but mechanisms and effects of F2BC have not been studied. We develop a plausible characterisation and model of F2BC and evaluate it in a simple scenario. To study F2BC in a naturalistic context we then reconstruct a consistent geometry for the Who concert disaster, explore the mechanisms for that disaster, and introduce F2BC. Our qualitative analysis suggests that F2BC can reduce injuries at the cost of lower exit rates.

1 Introduction

Crowd disasters frequently involve high pressures that cause crushing injuries and death by compressive asphyxia [1]. These pressures directly originate with crowd members as people within the crowd apply force through pushing and leaning; forces of over 4500 N have been observed in crowd disasters [1]. One might ask why these forces are applied, given their disastrous effects. Crowd research suggests that failures in front-to-back communication (F2BC) are common in crowd disasters [e.g. 1,2]. These failures occur when those applying force at the rear of a crowd do not know of important conditions (e.g. blocked exits, fallen people) at the front of a crowd. As forces become large, those at the rear also do not know that their actions are injuring those at the front.

A good example of a failure of F2BC occurred at the Who concert disaster at Riverfront Coliseum on December 3, 1979, in Cincinnati, Ohio. Eleven people died during ingress for unreserved seating before the concert. Johnson's analysis of the event suggests that people pushing at the rear of the crowd were unaware of problems at the front [3]. When the crowd surged forward to access the coliseum, about 25 people fell to the ground a short distance from an entrance. Despite the efforts of those around them to assist (or at least avoid) the fallen and to protect them from further assault, additional ranks of crowd members fell on top of them or were forced over them; the pile grew to 3–5 people deep at its worst, was 10–12 feet in diameter, and some people were lying on concrete for as long as 30 minutes. Those farther back (just 10 feet back according to one interviewee) were unaware of the situation and continued to push to gain access to the coliseum [3,4]. Although the media described the event as a stampede driven by mob psychology, Johnson found the opposite, that helping behaviours were widespread, even between strangers.

Although F2BC failures have long been suspected as a significant factor in the unfolding of a crowd disaster [e.g. 1,2], we have not found in the literature a systematic investigation of F2BC in crowds, neither its benefits nor

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model proposals. This means that although we hypothesize that increased F2BC would be helpful, we do not know the circumstances under which F2BC is possible or what benefit could be practically expected from employing it. We do not know whether situation-specific factors affect F2BC. The purpose of this paper is to begin to investigate some of these issues within the context of a microscopic crowd model. The principal contributions of this paper are the development of a F2BC model and its evaluation in both simple and realistic crowd situations.

The organization of the paper proceeds as follows. To begin we develop a characterisation of F2BC itself, as it has not previously been formally described. We then turn to the details of our implementation of this characterisation. We use the resulting simulation model to explore F2BC in a simple laboratory-like scenario. Wishing to consider how a more realistic scenario affects F2BC, we reconstruct the Who concert disaster in the model, making plausible observations concerning mechanisms of this disaster, and looking at those mechanisms when F2BC is added. We close with some preliminary conclusions on the nature of F2BC in crowds and proposals for further research work.

2 Characterising front-to-back communication

We are not aware of a study of F2BC in the literature – either a formal review of case studies or a theoretical discussion about how F2BC works within a crowd. In order to implement and study this phenomenon within a model, we need to specify a plausible mechanism for F2BC. Our mechanism is derived from the following premises, which underlie our hypotheses and understanding of F2BC in crowds.

1. *Initiation:* A person consciously initiates F2BC, based on stimuli that are cognitively available in the local environment. This occurs in response to a perceived threat to safety from an experienced strong force (e.g. resulting from external restriction of action). In other words, we suppose that people use the force they are experiencing in the crowd as a source of information, and use this information as the basis to initiate F2BC.

2. *Retransmission by dyads:* We take F2BC to be a distributed process of communication that involves direct personal interactions. Our supposition is informed, in this regard, by reports that yelling over a distance of 10 feet was impossible due to the noise at Riverfront Coliseum [3]. As in other confusing or noisy environments, successful communication requires 2 things: first, obtaining the attention of another individual, and second, directly communicating a simple message to them. Propagation of F2BC through the crowd depends on consecutive dyads repeating the information over time.

3. *Local information:* People in large crowds do not have an overall view of an unfolding crowd situation and may not know their exact position. They cannot be expected to know why others push or move in particular directions. Multiple points of attraction further confuse interpretation of movement and forces. Accordingly, we presume that, when we speak of front-to-back communication, '*back'* is not a global concept, and can only be determined locally. Each individual deduces this direction by considering the direction of incoming forces. Two people, even in close proximity, may conclude that the back of the crowd lies in different directions.

4. *Action:* People were powerless to avoid the fallen at Riverfront Coliseum [3]. Individual control can be lost in tightly packed crowds [1]. Given these constraints, we assume that people who are capable of voluntarily pushing can cease to do so, although their involuntary leaning forces cannot be controlled. Johnson reported a willingness to help [3], and we presume that this would be expressed by reducing determination to move to goal locations.

5. *Decay:* We suppose that people who are motivated to achieve a goal will co-operate with the actions described, but that people will not co-operate indefinitely. They will eventually return to normal individual behaviour, such as pursuing personal goals and including sensitivity to new incoming force and/or communication that would restart the F2BC cycle.

We acknowledge that in reality people would probably use several cognitive strategies to trigger initiation or decay of F2BC behaviours, likely including visual, auditory, movement and force cues. These cues could be noisy, uninformative, or could be valid only locally, being inappropriate judgements from a global perspective. Our model does not have facilities for these cues and judgements, but in keeping with the principles of microscopic human factors [5] we provide for an abstract representation of them.

By specifying our F2BC mechanism in the absence of data from real crowds, we leave open the possibility that these rules may not completely capture the behaviour of F2BC. However, our goal is a qualitative investigation (a quantitative model would require model parameters for which experimental measures have yet to be forthcoming). We believe that these premises are plausible for the purpose of evaluating the potential benefits of F2BC as well as the viability of person-to-person directed communication within a crowd.

3 Modelling front-to-back communication

It is our continuing view that microscopic crowd models can help to shed light on the workings of crowds by examining how interactions at the level of the individual (microscopic level) combine to create emergent crowd effects (macroscopic level). In a microscopic crowd model, behaviour is modelled from the point of view of individual crowd members. In principle, each modelled individual (agent) in the crowd can draw on its own experience and local observations, applying its rules of behaviour to determine desired actions. This individual modelling paradigm is well suited to studying the movement of information in a crowd. Agents can in principle have internal memory, a sense of their immediate surroundings, and the ability to communicate with each other. Particular models imbue agents with the particular capacities required to implement the social behaviours required. In a simple microscopic model, we can establish a causal connection between emergent global level behaviours and the rules and capacities of individual agents.

The floor field model (FFM) [6] is a cellular automaton and microscopic crowd model of individuals on a 2 dimensional grid. Agents interact according to a neighbourhood defined by the cardinal compass directions and move according to local rules, balancing their movement decisions between reducing their distance from desired goals on a mental map of the environment and following other nearby agents. FFM as originally specified does not provide for individual cognition beyond the interaction of the 2 perceptions just described, or for physical force between and upon agents. We view it as an ideal starting point for a multi-agent system that can easily include additional agent capabilities such as memory, direct communication and reflection before action, all required by our characterisation of F2BC. We have previously extended the model to include force and injuries [7], required to model crowd safety in crush conditions and to provide the motivation for F2BC. We have also extended the model to study direct agent communication in milling [8] and that communication model has also contributed to this work.

3.1 The floor field model

In FFM, agents have a single action: they move. They are initially distributed at random on a grid that provides a co-ordinate system both for movement and for maps of information available to agents called *fields*. Fields are so-named due to their analogy with physical fields, carrying information accessible to agents based on their position on the grid, used in making movement decisions. The model provides for two fields: the *static* field and the *dynamic* field. The static field – in an in/egress scenario – encodes the distance from the agent to the nearest entrance/exit. This definition can be fulfilled according to several different metrics, with different simulation dynamics resulting [9,10]. Agents consult the values of the static field in cells neighbouring their current location in order to follow a gradient towards the exit. A second, *dynamic*, field provides a mechanism for agents to become aware of the movement of other agents by analogy with ant pheromone chemotaxis. Each agent leaving a cell drops *dynamic bosons*, which have a dynamics by which they diffuse to neighbouring cells and decay with a certain probability each time step. Agents can consult the values of the dynamic field in cells neighbouring their current location in order to follow "paths" left by previous agents.

In reality people do not have perfect information concerning the movement of others, and the location of points of interest. The model provides for sensitivity parameters that agents multiply with the values of the static and dynamic fields to obtain a measure of the desirability of a cell:

$$\mathit{desirability} = \exp(k_D D_{ij})\exp(k_S S_{ij})(1 - n_{ij})\xi_{ij} \qquad (1)$$

Here, k_S and k_D are the sensitivity parameters for the static field, S, and the dynamic field, D. By providing for a high k_S relative to k_D, an agent values movement to the exit more than following others – perhaps simulating a knowledgeable agent with a definite goal. With a low k_S relative to k_D, the agent will tend to follow others more than aim for an exit – perhaps like a visitor to an unfamiliar space with poor lighting. When k_S and k_D are both low, the agent tends not to prefer one cell to another. The value n_{ij} is 1 (0 for occupied cells), and the value ξ_{ij} is 1 (0 for walls). When making a movement decision, the agent considers the desirability of each neighbouring cell; the probability of selecting a neighbour is proportional to its desirability.

Agent movement is synchronous. Only one agent may occupy a cell at a time; conflicts in the original FFM are resolved randomly. Of course, it is also possible that a cell occupied by a stationary agent will be selected, in which case an agent desiring that cell must remain stationary as well.

3.2 The swarm force model

Our swarm force model (SFM) is an agent-based derivative of FFM. In this model agents are provided with a further action, that of pushing. Force in SFM is represented by a third floor field. Agents that attempt to move to a cell and find it blocked will perform *voluntary pushing* in which they deposit onto their cell *force bosons:* vector particles with unit magnitude and having the same direction as the agent intended to move. Like the dynamic field, the force field also evolves with time. Between time steps, the force field propagates: the vector sum of bosons on each cell is calculated, the force direction is quantized toward one of the four neighbours, and then deposited on that neighbouring cell. Empty cells, wall cells and cells with injured agents (see below) absorb force and do not re-propagate it.

Force carries two consequences. First, agents that experience force above a particular threshold, $f_{nochoice}$, lose control over their choice of cells. These agents are required to select cells in the direction of the force. (If the required cell is not available at movement time, the agent will push. The mechanism for this is identical to voluntary pushing, but in this case the pushing is termed *involuntary*, and is intended to represent a leaning force.) Second, agents that experience force above a higher threshold, f_{crush}, become injured. These agents stop moving, do not participate in any form of communication, and are essentially treated as new wall cells. It should be noted that both of these force thresholds are measured against the scalar force on the agent's cell rather than the vector force that is calculated during field propagation.

3.3 Front-to-back communication in the swarm force model

The four key processes of initiation, action, retransmission and decay are implemented as follows in our F2BC simulation.

1. Initiation: Initiation of F2BC occurs when the local scalar force rises above the $f_{nochoice}$ threshold[1]. Similarly to communication in our swarm information model [8], a direct agent-to-agent communication is used. Agents deliver a simple signal toward the back. In accordance with the *local information* premise, this is defined locally as the direction opposite to the quantized vector sum of force bosons present. The receiving agent, if any, accepts the communication with probability $p_{receive}$. Otherwise the agent is deemed not to have heard the communication, or to have heard it but to have decided not to comply. Agents who initiate F2BC and continue to experience force above the threshold may initiate again on the next time step.

2. Action: An agent initiating or accepting F2BC will take action in two ways. First, a new factor multiplying k_S in eq. (1) changes from 1 to 0. This m_S factor dynamically eliminates the receiving agent's desire to move toward exits by decreasing the static field's importance, consequently reducing pressure on the originating agent. Second, the agent refrains from voluntary pushing. Involuntary pushing continues as normal, as does normal propagation of existing force. This yields a new desirability equation (SFM replaces n_{ij} with ϕ_{ij}: 1, except 0.5 for occupied *ij*. See [7] for a discussion of this point):

$$desirability = \exp(k_D D_{ij}) \exp(m_S k_S S_{ij})(1 - \phi_{ij})\xi_{ij} \qquad (2)$$

3. Retransmission: An agent that receives one or more F2BC signals in a particular time step will consider, with probability $p_{retrans}$, retransmitting one signal to another agent on the subsequent time step only. Retransmission only

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[1] The initiation threshold was formerly f_{crush} / 2. This value, well beyond agents' loss of movement control, conflicted with our premise that agents cognitively decide to initiate based on feeling unsafe, and promoted very late initiation of F2BC. We now base initiation on loss of control.

occurs if the scalar force present on the retransmitting agent's cell exceeds its pushing force. In accordance with the *local information* premise, a retransmitting agent reverses the force vector on its own cell to determine which way appears 'back'. Communication then occurs identically to initiation.

4. Decay: Agents acting upon F2BC signals have a probability, p_{decay}, in each time step of returning to normal behaviour. Normal behaviour involves a resumption of voluntary pushing, and cell selection with $m_S = 1$.

4 Laboratory scenario

We have evaluated the proposed F2BC model using two different scenarios, a simple laboratory-type scenario and a realistic scenario. The laboratory scenario utilises parameters used by previous investigations into FFM and SFM [6,7]. The space consists of a grid of 61 x 61 cells encircled by wall cells – excepting one exit cell located in the middle of the front wall. The space is filled 30% full with agents distributed randomly. Additional fixed parameters: α and δ (dynamic boson diffusion and decay probabilities) 0.3, agent pushing force ρ drawn from a normal distribution with $\overline{\rho} = 5$, $\sigma = 1$. $f_{nochoice} = 3\rho$. In these trials $p_{receive}$ and $p_{retrans}$ are set to 1, while $p_{decay} = 0.1$.

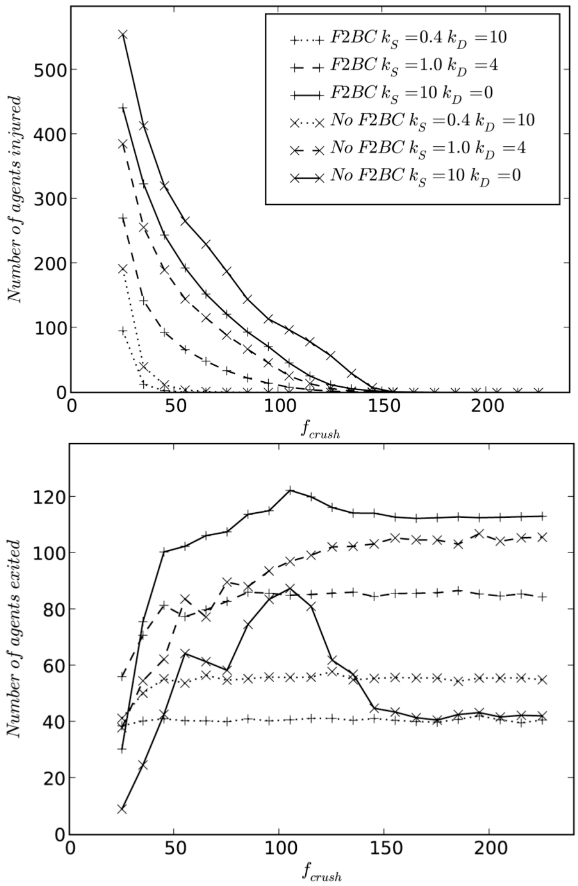

Fig. 1 (a) agents injured vs. f_{crush} (b) agents exiting vs. f_{crush} (same legend)

We used the three combinations of k_S and k_D values used in the egress analysis of FFM [11], and also varied the threshold for agent injury, f_{crush}, from a very low threshold (easy to become injured) to a very high threshold (difficult to become injured). We counted the number of agents exiting the space and the number of agents injured in 350 time steps of the model, repeating each trial 50 times, averaged results shown in figure 1.

The injury results, shown in figure 1a, demonstrate that introduction of F2BC into a laboratory-type scenario does reduce injuries, regardless of whether agents are motivated to exit quickly, to follow others, or to strike a balance between the two options.

An important question that arises from these results is how exit rates are affected by the reduction in injury rates. Figure 1b indicates that F2BC does affect the exit rate. When $k_S = 0.4$ and $k_D = 10$ agents are primarily guided by the movement of others. In this case the drive to exit and crowd density remain low [7], injuries are not a significant factor, and F2BC further slows what is already a non-urgent exit from the space. When $k_S = 1$ and $k_D = 4$ again the dominant factor is other-agent movement, although movement toward the exit is much facilitated by the increasing ratio $k_S : k_D$. Crowd density and drive to the exit are moderate [7]. Introducing F2BC improves the exit rate when agents are easily crushed, largely due to a postponement in injuries that allows more agents through the exit before it becomes clogged with injuries. When agents are more robust, numbers of injuries drop, revealing that – in the absence of injuries – the tendency of F2BC to produce a more patient crowd results in lower exit rates. The third case, in which $k_S >> k_D$, tends to produces fast movement toward the exit, high crowd densities, and large forces [7]. In this case F2BC both reduced injuries and also resulted in a faster exit.

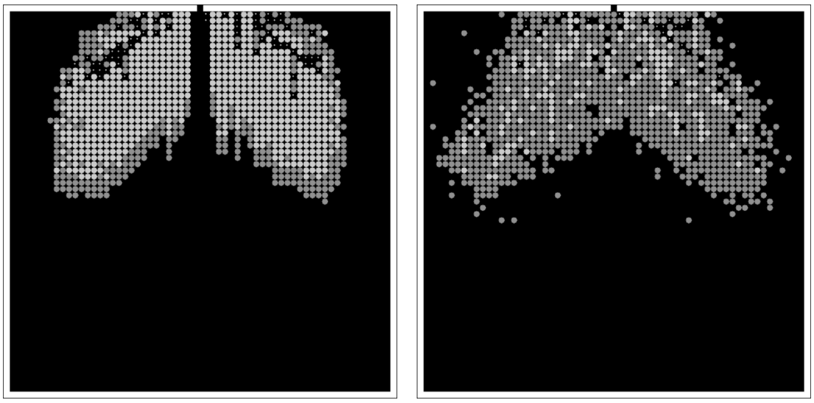

Fig. 2 Disappearance of aisle region. Light grey agents exceed $f_{nochoice}$ threshold, small dots indicate injured agents. (a) no F2BC (b) with F2BC. (Both with $k_S = 10$, $k_D = 0$, $f_{crush} = 105$, time step = 127)

This third case, in which the exit rate is facilitated, is quite interesting in the context of earlier work on this scenario. In the original examination of SFM [7] we found that high pressures in the crowd led to a formation called the aisle – a region centred on the door extending from the front to the back of the crowd in which agents are able to exit even under high pressure (figure 2a). By contrast, agents adjacent to the aisle are not able to choose a lateral step into the aisle because the forward pressure upon them exceeds $f_{nochoice}$ and they are pinned in place. A stable configuration of this sort greatly decreases the exit rate. When injuries were introduced into the model an interaction emerged between f_{crush} and the exit rate in which moderate f_{crush} values (circa 100 in figure 1b) provoke moderate numbers of injuries. These injuries provide force-breaks within the crowd, resulting in the best exit rates. Just forward of these breaks agents are free to choose their own cells, and can step into the aisle. This breaks the stable configuration and allows more agents to exit. When f_{crush} is low, too many agents become injured, hampering the exit rate. With high f_{crush}, no force breaks form and the aisle pattern remains.

When we introduce F2BC into the model the aisle pattern disappears. The results of figure 1b, along with observations we have made of the model, suggest that F2BC is an alternative to force breaks in facilitating exits in high-pressure egress. When F2BC occurs within the crowd, agents effectively communicate with those behind them, reducing the pressure below their $f_{nochoice}$ threshold. This prevents aisle creation as agents control the force upon them sufficiently to allow the lateral steps that they would otherwise be prevented from making. With no force breaks required, high f_{crush} values (when injuries drop to zero) do not impede the exit rate and the aisle is not formed (see figure 2b). Low f_{crush} values continue to produce high numbers of injuries and a consequent decrease in exit rate through clogging of the exit area by injuries.

5 Who concert disaster scenario

In order to provide further support for the hypothesis that F2BC can improve crowd dynamics, we wanted to evaluate the effect that F2BC could have in a non-laboratory situation. We chose to simulate the Riverfront coliseum concert disaster because of an encouraging and detailed account of communication and social behaviour [3], and the good descriptions of the physical surroundings and events [3,4].

5.1 Reconstructing the plaza at Riverfront Coliseum

The plaza of the coliseum has been altered since the time of the disaster, however we attempted to reconstruct its physical dimensions based on three sources: a news photo taken the night of the disaster [12], an aerial photo of the original plaza and building [13] and figure 3. (Hereinafter, all reference marks are to figure 3.) Despite perspective effects, we were able to produce a consistent plaza geometry.

Photo [12] of location *A* shows a bank of 8 doors. We supposed these doors were full size (914 mm) establishing our scale. Photo [12] also shows a large squarish column (~4 doors wide) at *i*, and a smaller column (~1 door wide) at the building-lobby junction near *A* (call this *BLJ*). These estimates fix the length of wall *A* at 11.8 m. The view of the doors at *B* in [12] is partially obstructed, but we suppose that there were 8 identical doors there, flanked by column *i* and an identical column, setting wall *B* at 14.6 m long. The wall measures set the scale for figure 3 (used for all front-to-back estimations, scale set from length of *A*) and photo [14] (used for all side-to-side estimations, scale set from the doors at *B*). The model's x-axis is parallel to wall *B*; the model's y-axis is parallel to wall *A*.

The lookout at the right of the plaza is an isosceles trapezoid with height 3.9 m, whose parallel sides measure 37.1 m and 44.6 m. Remaining side-to-side dimensions (all projected onto the x axis) are: *BLJ* to *E* 17.7 m, *E* to *ii* 4.9 m, ramp width 15.6 m. Remaining front-to-back dimensions (all projected onto the y axis) are: *ii* to *F* 17.8 m, *BLJ* to *iii* 47.5 m, *E* to *BLJ* 10.9 m, the wall of *C* opposite *A* is 5.9 m.

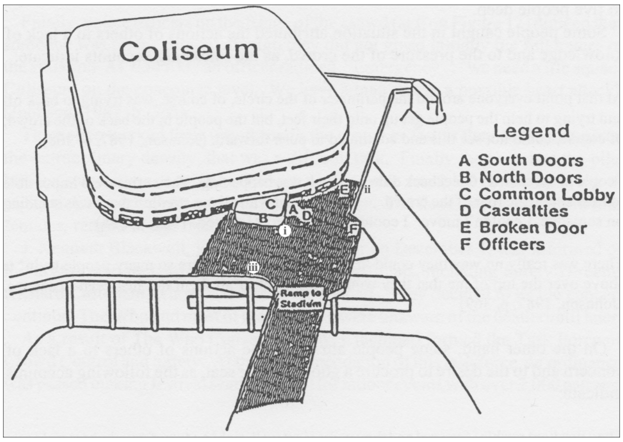

Fig. 3 Plaza at Riverfront Coliseum. Lower-case reference marks ours. (Used by permission of NR. Johnson and University of California Press, from [3]; permission conveyed through Copyright Clearance Center, Inc.)

Although units of space, time and pressure in SFM are not calibrated to real-world units, we needed to set the size of a grid cell. We chose 56 cm, the commonly cited (if dated) reference human body width [14]. The above estimates were quite consistent, only requiring minor adjustments of ±1 cell to make the various structures line up correctly. The 56 cm cell implies approximately 13 cells per bank of 8 doors. We interpreted remarks that insufficient doors were open by supposing that half of the doors were open, so we have included 6 exit cells in the centre of each bank.

Although a police officer inside the coliseum reported "there must be 8000 people standing on the outside trying to get in," [3] we feel from the description of the officer's circumstances that this was conjecture rather than a reliable estimation. Given our estimates and our square grid cells, 5000 agents provided a very high density sufficient for our purposes. We distributed agents randomly within the shaded (high density) area of figure 3.

5.2 Analysis of the disaster

We ran the simulation using the same settings used in the laboratory experiments, except that we fixed k_S and k_D at 1.0 and 0.5 respectively. We sampled a range of f_{crush} values from 100 to 300, with and without the F2BC simulation active, for the first 350 time steps of model execution.

First we consider the coliseum scenario without F2BC enabled. We found that forces were high and the scenario was prone to producing injuries. In such a large scenario injury thresholds have a strong effect on injury distribution. This is because, at low values of f_{crush}, agents rapidly become injured throughout the crowd due to relatively small numbers of other agents required to inflict damage (see figure 4a). In SFM injured agents throughout the crowd prevent force from propagating over long distances. When the f_{crush} parameter is higher, injuries are more focused because many ranks of agents are required to generate the cumulative forces required to cause injuries.

In observing the simulation, we noted that injuries tend to appear first at certain force hotspots, particularly when the geometry and lack of intermediate force breaks allowed many ranks of agents to generate large cumulative forces over significant distances. An additional facilitating factor for injury involves a scenario where force can move in two directions. While conscious of the fact that our model is only a qualitative simulation and reconstruction from secondary sources, our observations of the simulation suggest that the area around *D* (where injuries occurred in the real disaster) is particularly prone to being a site for injuries once long range forces can build up (figure 4b). This occurs because pushing and leaning forces originating from those exiting the ramp can proceed unimpeded to *D*, with many ranks pushing in this direction. In the simulation, agents near the ramp pushing forward quickly overwhelmed the free choice of agents in front of them on the plaza, forcing them to add their pushing and leaning forces toward *D* rather than allowing some to aim for *B*. Compounding this, agents near the coliseum end of the lookout generate additional perpendicular forces toward *D*.

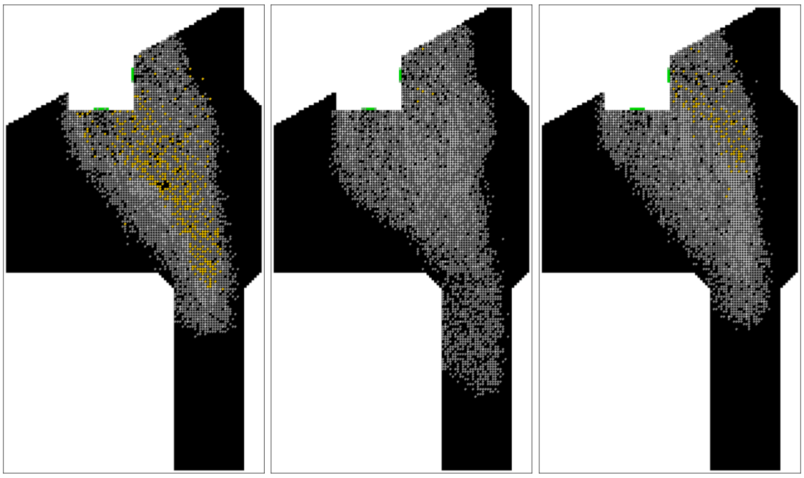

Fig. 4 Riverfront Coliseum scenario. Exits cells are green, agents are grey, agents beyond $f_{nochoice}$ are light grey, injured agents are yellow. (a) f_{crush} = 100, time 350 (b) f_{crush} = 210 time 161 (c) f_{crush} = 210 time 350

When these forces continue to be applied at a high level, our model shows injuries continuing to propagate from the area around *D* onto the plaza, toward the ramp (figure 4c). This continuing propagation onto the plaza was not reported in the disaster. We note here three possible reasons for this discrepancy. First, SFM does not distinguish between fatal and non-fatal injuries; non-fatal injuries in the crowd at this event are poorly documented and there may indeed have been high forces propagating to these locations. Second, other non-modelled factors in the scenario (e.g. the sudden increase in drive toward the exits brought on by the band's warm up) may be relevant in limiting peak injuring forces to particular time periods. Third, it may simply be that SFM, a fairly abstract force model, lacks the fidelity to model additional dissipative factors that prevented injury in these locations despite continuous pushing.

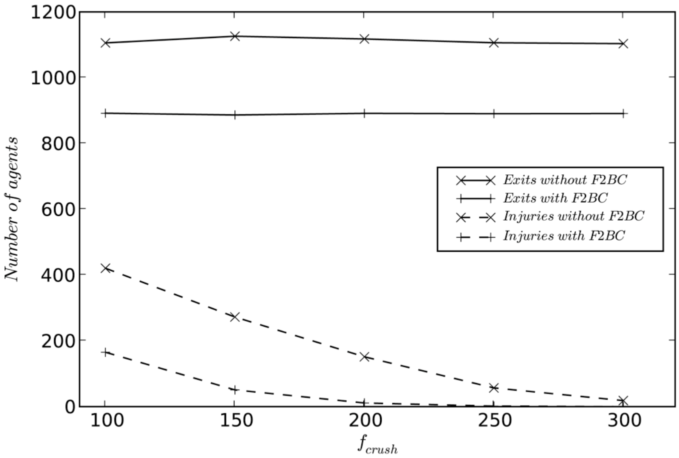

Fig. 5 Agents exited and injured in the Riverfront Coliseum scenario

We then enabled the F2BC simulation in the Riverfront Coliseum scenario. We carried out 50 runs per data point, and the averaged results, both for exits and injuries, are shown in figure 5.

We found that, as with the laboratory scenario, agents were able to control forces over a long distance, substantially reducing the number of injuries. As the lobby was the movement goal for agents, it is not surprising that at high values of f_{crush} (when injuries are low) remaining injuries occur in this area. Observations of the model suggest injuries were more distributed, with hotspots for injuries near *i*, near the exits and between *A* and *E*.

We found that injuries within the model did not have an impact on egress rate. As f_{crush} increased, making agents less susceptible to injuries, exit rates remained constant. Introducing F2BC into the model resulted in a more patient, less forceful crowd. This had a consequent effect to decrease the exit rate, which was also unaffected by numbers of injuries.

6 Conclusion

Noting that failures of front-to-back communication are commonly cited as important factors in crowd disasters, our goal was to study this phenomenon within a microscopic model to determine what potential benefits F2BC may provide, and the effect of introducing F2BC into a crowd situation. We have proposed a model of F2BC that includes: initiation based on a loss of individual movement control, retransmission through successive dyads, behaviour modification for parties to the communication in the form of reduced voluntary pushing and movement drive, and a time-based method of decay of this behaviour modification. We implemented this conception of F2BC by extending SFM [7], itself a variant of FFM [6]. Our results suggest that F2BC does have the potential to reduce damaging forces in a laboratory scenario, at the cost of reducing the exit rate due to increased patience.

To evaluate F2BC in the context of a more realistic scenario, we reconstructed the geometry of the plaza at Riverfront Coliseum in Cincinnati, Ohio that witnessed the Who concert disaster of December 1979. We based our approximation of this space on secondary sources such as published diagrams and photos available on the internet, and obtained a consistent conformation. Although our simulation is designed to obtain qualitative results relating to the introduction of F2BC we found that our model predicted a force hotspot, with subsequent agent injuries, in the same area that saw real injuries in 1979. The results suggest that forces built up over a long distance from the plaza ramp toward the coliseum, and were compounded by perpendicular forces from the plaza lookout. When we added F2BC the number of injuries decreased substantially, as did the exit rate. These results suggest that F2BC may be protective in crowd situations.

Although the model contains parameters that can tune the degree to which agents co-operate in F2BC, the present work has not considered changes to these parameters, instead supposing full compliance with the protocol. In future work we plan to establish the degree of compliance required for benefits to occur, and whether benefits degrade smoothly with a decrease in compliance. We also note that unlike at the Who concert tragedy, many crowd venues now have voice communication systems and overview facilities for trained crowd management personnel. We would like to consider the interactions that global information and communication may have with F2BC in a crowd situation.

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