AN ANALYSIS OF ANGLED-CORRIDOR EFFECT ON PEDESTRIAN WALKING BEHAVIOUR FOR CROWD DYNAMICS SIMULATIONS

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UNIVERSITI SAINS MALAYSIA

2019

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by

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Thesis submitted in fulfillment of the

requirements for the degree of

Master of Science

October 2019

ACKNOWLEDGEMENT

In the name of Allah S.W.T., the most gracious and most merciful, I thank Him for the blessing, protecting, and guiding throughout this period of Master of Science study. I would like to express my profound sense of reverence to all those people who had helped me, directly or indirectly, to complete my master course study and made this thesis possible.

At this moment of accomplishment, I would like to pay homage to my great supervisor, Dr. Noorhazlinda Abd Rahman for her willingness of accepting me as her student in the first place, and her kindness for giving me the opportunity to work and gain countless of experiences and insights under her supervision.

I am extremely indebted to my supervisor, for her valuable advice and her extensive discussions around my work. Not to forget, her continuous efforts in boosting my morale throughout the course of research and being available to guide me in all my research works. Thank you for facilitating my works especially in terms of the provision of all necessary equipment and resources to accomplish my research work. I will always cherish her in my future endeavour.

I also would like to acknowledge my family, especially my father, Alias Bin Ibrahim and mother, Azizah Binti Omar for always supporting and advising me to pursue my study in master’s level. To my lovely siblings, Syahida, Shahril, and Hazwani thank you for giving me the much needed moral support during the ups and downs of my study. And lastly, to my beloved husband Muhammad Athif, thank you for being patient and understanding throughout.

Not to forget, I would also like to give credit to the lecturers, staff, and technician of Pusat Pengajian Kejuruteraan Awam (PPKA) for their direct and indirect helpful hand. I will always be grateful to them for helping me during my research as well as for all the useful advices. Lastly, to my best friends forever, Atikah, Mastura, and Anis, who are always excited to lend their ears to hear my success stories and for inspiring me to perform better, thank you.

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LIST OF ABBREVIATIONS

AAE	Adobe After Effect
CBS-DE	Crowd Behavior Simulator for Disaster Evacuation
DEM	Distinct-Element-Method
FEM	Finite-Element-Method
HBS	Human Behavior Simulator
HCM	Highway Capacity Manual
NOP	Number of Pedestrian
NEP	Number of Escape Pedestrian
UBBL	Uniform Building by Law

LIST OF SYMBOLS

v	Velocity
t	Time
v_x	Velocity in x direction
v_y	Velocity in y direction
Δx	Difference in x direction
Δy	Difference in y direction
Δt	Difference in time
m_{hi}	Mass of person i
I_{hi}	Moment of inertia of person i
v_{hi}	Velocity of person i
F_{awhi}	Driving Force of person i
F_{inhi}	Inter-element force acting on person i
ω_{hi}	Angular velocity of person i
T_{hi}	Torque acting on person i
v_{limit}	Specific equilibrium velocity
V_{max}	Maximum velocity
γ	Proportional coefficient
C_k	Density of person inside the perception domain
F_{ij}	Physical repulsive force between person I and person j
F_{iw}	Physical repulsive force between a virtual wall element W and person i
F_{psij}	Psychological repulsive force acting between person i
f_{ij}	Local physical repulsive force acting between person i and person j

f_{iw} Local physical repulsive force acting between person *i* and virtual wall element *W*

f_{psij} Local psychological repulsive force acting between person *i* and person *j*

r_i Positional vector of the person *i*

r_w Positional vector of the virtual wall element *W*

ANALISIS KESAN LALUAN BERSUDUT KE ATAS PERILAKU PEJALAN KAKI UNTUK SIMULASI DINAMIK ORANG RAMAI

ABSTRAK

Koridor dengan sudut atau dikenali sebagai koridor bersudut, adalah salah satu keadaan geometri dan kemudahan yang boleh mencetuskan sekatan aliran pejalan kaki dan menyebabkan kesesakan ketika suasana sibuk. Terdapat beberapa faktor yang membawa kepada kesesakan di koridor, seperti sudut koridor, jarak trek, ketumpatan pejalan kaki, arah aliran, lebar koridor, struktur bangunan, dan kesan psikologi.

Tesis ini fokus kepada kesan koridor bersudut ke atas tingkah laku pejalan kaki. Kajian ini dijalankan dengan tujuan untuk menentukan secara empirikal hubungan antara halaju berjalan dan ketumpatan pejalan kaki bagi aliran bebas satu arah di koridor bersudut untuk menentukan ambang bilangan pejalan kaki dan koridor bersudut yang bersesuaian yang berkaitan dengan bilangan pejalan kaki yang berlainan, di mana masa pelepasan menurun pesat kerana kemerosotan tingkah laku kesesakan berhampiran sudut.

Selanjutnya dari kedua-dua tujuan utama yang disebutkan, masa keluar dianggarkan dengan meniru senario hipotetikal berjalan di koridor bersudut dengan mempertimbangkan dua faktor: (1) bilangan pejalan kaki yang berlainan, dan (2) sudut koridor berbeza. Terdapat dua bahagian utama yang terlibat dalam kajian ini, iaitu kerja-kerja eksperimen dan simulasi. Eksperimen pejalan kaki berjalan melalui tiga koridor bersudut (60°, 90°, dan 135°) yang dibina telah dijalankan di Dewan Serbaguna, Kampus Kejuruteraan, Universiti Sains Malaysia. Sementara itu, simulasi senario hipotetikal berjalan keluar di koridor bersudut dilakukan berdasarkan bilangan pejalan kaki dan sudut koridor yang berlainan. Bagi kerja simulasi, perisian MAYA

dan Simulator Kelakuan Orang Ramai untuk Pemindahan Bencana (CBS-DE) telah digunakan.

Hasil dapatan menunjukkan purata halaju berjalan adalah berkadar songsang dengan bilangan pejalan kaki. Memandangkan bilangan pejalan kaki melintasi koridor meningkat, jumlah ruang kosong yang tersedia menjadi terhad, oleh itu purata halaju berjalan menurun akibat pergerakan individu dihadkan. Ini seterusnya menjejaskan masa perjalanan.

Dapatan yang diperoleh dari simulasi adalah masa dan daya interaksi. Dapat diperhatikan hampir semua simulasi menunjukkan koridor bersudut 60° mencatatkan masa berjalan keluar terpanjang, manakala koridor bersudut 135° menunjukkan masa egress paling rendah. Juga dapat dilihat dari kedua-dua keputusan titik infleksi dan kesan penolakan menunjukkan bahawa koridor bersudut 60° mempunyai bilangan tertinggi terhadap titik infleksi dan kesan penolakan berbanding koridor bersudut yang lain. Ini menunjukkan bahawa koridor dengan sudut kurang daripada 90° perlu dielakkan semasa merancang koridor bersudut kerana ia secara jelas meningkatkan masa berjalan keluar.

Keputusan yang diperoleh daripada kajian ini dijangka menjadi pangkalan data dan bahan rujukan yang berguna untuk mereka bentuk dan mendimensi kemudahan pejalan kaki masa depan yang melibatkan koridor dengan sudut dan bentuk yang berbeza-beza. Pada masa akan datang, kajian ini perlu diteruskan dengan mempertimbangkan senario yang lebih pelbagai dan terperinci yang berkaitan dengan perubahan gerakan di koridor yang lebih berbeza.

AN ANALYSIS OF ANGLED-CORRIDOR EFFECT ON PEDESTRIAN WALKING BEHAVIOUR FOR CROWD DYNAMICS SIMULATIONS

ABSTRACT

Corridor with angle or known as angled-corridor is one of the geometrical condition or facilities that could trigger restrictions to pedestrian flow and causing congestion during rush hour. There are a few factors that lead to the occurrence of congestion at the corridor, for instance, the degree of a corridor, track distance, density of the pedestrian, nature of direction flow, width of the corridor, building structure, and psychological effect.

This thesis focuses on the effect of angled-corridor on pedestrian walking behaviour. This study was conducted with the aim to determine empirically the relationship between pedestrian velocity and density of pedestrian empirically unidirectional free flow by focusing the angled-corridors. Next, this study also aim to determine the threshold number of pedestrian and corresponding angled-corridor related to different number of pedestrian, beyond which the egress time can be decrease rapidly due to a strong degradations of congestion behaviour near the corner.

Further from the two main objectives mentioned, the egress time were estimated by simulating hypothetical walking scenarios at the angled-corridor by considering two factors: (1) different number of pedestrian, and (2) different angle of corridor. There were two main parts involved in this study, which are the experimental work and simulation work. The experiment of pedestrian walking through three different built angled-corridor facilities (60°, 90°, and 135°) were conducted at Dewan Serbaguna, Engineering Campus, Universiti Sains Malaysia. Meanwhile, the

simulation work of hypothetical egress scenario at angled-corridor was carried out based on different number of pedestrian and different angle of corridor. For the simulation work, MAYA software and Crowd Behaviour Simulator for Disaster Evacuation (CBS-DE) has been employed.

From the obtained results, the average walking velocity of pedestrian was inversely proportional to the number of pedestrian. As the number of pedestrian traversing the angled-corridor increase, the amount of free space available becomes limited, hence the average walking velocity decrease due to the movement of individual is being restricted. This subsequently affects the travel time.

Results obtained from simulation work were egress time and interaction force. It can be observed that almost all simulation in correspondence to angled-corridor 60° recorded the longest egress time, while angled-corridor 135° shows the least egress time. Also, noted that both results for inflexion points and repulsion effect had shown that the angled-corridor 60° had the highest number of inflexion points and repulsion effect compared to the other angled-corridor. This indicate that corridor with angle less than 90° should be avoid while designing angled-corridor as it explicitly increase the egress time.

The results obtain from this research are expected to be a useful database and tool for designing and dimensioning of future pedestrian facilities which involves corridor with varying angles and shape. In the future, this study should be further continue by considering more varied and detailed scenarios associated with turning movement at more different angled corridor.

CHAPTER ONE

INTRODUCTION

1.1 Background

Angled-corridors, as known as corner among the civilian are common geometrical shapes found in pedestrian walkways constructed within public's facilities, and most buildings. The angled-corridors that are being used as egress routes are obviously becoming one of the important features that require precisely accentuated design, since that kind of corridors affect the turning motion of pedestrian that uses the walkways. Logically, we can assume that there will be changes to the human walking velocity when they are approaching and walking through the angled-corridor. This is due to the turning motion that takes place when the pedestrian is near the angled-corridor and this subsequently triggers restriction on pedestrian flow. Thorough understanding of pedestrian flow for any geometrical shape in a specific building is crucial since it is a basis in determining and evaluating the characteristics of walking pedestrian.

The investigation on the effect of angled-corridor on human walking behaviour was rarely studied as compared to the other types of facilities such as straight corridors and T-shaped intersection. A research by Zhang et al. (2011) has shown a series of well-controlled laboratory experiment conducted for T-junction to investigate the flow of pedestrians before and after the merging. The results from the experiment found that the flow of pedestrians in the T-junction were not identical prior and post merging.

Effect of different type of angled-corridors on the walking behaviour of pedestrian by postulating microscopically should be further studied since the empirical relation between density and velocity of pedestrian motion in relation to pedestrian interaction, which determine the relation at low, medium, and high densities, is not completely analysed. Furthermore, the design and layout of corridors tend to be more complex, and sophisticated of the construction of varied degrees of angled-corridor with the exception of right-angled walkways are often seen incorporated in new buildings. Therefore, proper consideration should be given to properly plan and design the feature of egress route different angled-corridors other than right-angled of corners.

To facilitate this study, a microscopic particle-based model which is the Distinct Element Method (DEM) - based Crowd Behaviour Simulator for Disaster Evacuation (CBS-DE) is utilised. The model is capable of modelling each pedestrian distinctly by tracking the trajectory and rotation of each pedestrian in the domain. Crowd Behaviour Simulator for Disaster Evacuation (CBS-DE) has been developed at the Laboratory Professor Hitoshi Gotoh in Kyoto University , Gotoh et al. (2008). It has been used in many studies on evacuation processes and crowd behaviour. In this study the simulator is used to simulate the senario of pedestrian walking through different angled-corridors.

1.2 Problem statement

For many years, the study of crowd dynamics through several crowd behaviour model has been a spectacular developed. This is related to the lack of human interest and human awareness of the importance in implementing good egress behavior. Thus, the analysis of crowd dynamic has become more vital than ever. In this dissertation, the analysis mainly focuses on the analysis of the effects of angled- corridors on velocity of pedestrians, and also egress behaviour.

Corridors with angle or known as angled-corridor, is one of the geometrical condition or facilities that could trigger restrictions to pedestrian flow and causing clogging and congestion during rush hour, Dias et al. (2014). There are numerous reasons that lead to the occurrence of congestion at the corridor with angle facilities, for instance, the degree of a corridor, track distance, density of the pedestrians, nature of direction flow (uni- or bi-directional), width of the corridor, structure of the building, and psychological effect, Guo and Tang (2012).

Large crowd can be occurred in the public infrastructure due to the daily activities, cultural, or sport event. Hence, there is a possibility an accident might occurred during emergency situation when the evacuees are trying to evacuate the building when passing through the angled-corridor, if no proper consideration during the planning and designing process prior constructing the angled corridor. The safety of people are extremely important in case of emergency and to make sure that the flow of movement become more efficient in day-to-day situations. Thus, it is important to note the significance of precise planning and designing works as it helps to improve the safety, efficiency, and comfortable level of crowded evacuation in a building.

1.3 Objectives

The objective of this study are listed below:

1. To determine the relationship between velocity and density of pedestrian, for unidirectional free flows at angled-corridors in building structure.
2. To determine the threshold of angled-corridors corresponding to inflexion point involving different number of pedestrian.

3. To numerically estimate egress time and interaction force by simulating hypothetical walking scenarios at the corner in a building based on two parameters: (a) different pedestrian density, and (b) different angle of corridor

1.4 Scope of Study

The implementation strategies of this study are two-pronged which is experimental and simulation works. Experimental work involved the uni-directional flow experiment of walking pedestrian at three different types of angled-corridors. The three different types of angled-corridor consist of 60°, 90°, and 135° were studied for different number of pedestrians. Experiment is to be set up under well controlled environment so that it will be able to reproduce pedestrian dynamics in a realistic way. The empirical result obtained are used to verify the reliability of the model.

Secondly, numerical simulation of hypothetical egress scenarios at the angled-corridor are performed for different number of pedestrian (medium to high) and different angled-corridors. This study examines the effect of angled-corridor on egress behaviour during emergency building egress by using CBS tool (in house developed tool) and Autodesk® MAYA® 2016 (MAYA) for experiment based analysis, modelling and simulation. To facilitate this study, a CBS-DE model is employed to simulate the egress process in a building under the implementation different number of pedestrian and angle of the corridor. From this simulation, the egress time and repulsion effects (interaction repulsive force) can be obtained and analysed.

1.5 Significant of Study

The results obtained from this research are expected to be a useful database and tool for designing and dimensioning for the future pedestrian facilities which involves corridor with varying angles and shapes. This can be contributed towards the implementation of better corridor design and enhance the emergency response plan. The threshold density can help in limiting the number of pedestrian at the angled-corridor during evacuation to increase the efficiency of evacuation process and at the same time reduce potential accidents from occur during emergency egress. This study also may be helpful in determining the corresponding critical angled-corridors related to different density of pedestrians for evacuation efficiencies in order to improve the safety and comfort ability level of crowded evacuation in building.

1.6 Dissertation Outline

In this dissertation, brief introduction and overview of the study are explained in Chapter 1, which includes the background, problem statement, objective, scope of study, and significance of study. Chapter 2 contained the literature review, at which further discussions and comparison are done between priory conducted studies that are in relation with the current study. Chapter 3, mainly described the procedure for data collection and methodology deployed in achieving study objectives. The findings from experimental and numerical work were discussed in Chapter 4. Finally, conclusion and recommendation are highlighted in Chapter 5.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In this chapter, the fundamentals of angled corridor geometry including the behaviour of walking pedestrian and the resulted trajectories of the pedestrian were described based on different type of walkways. This chapter also discusses on the walking velocity of the pedestrians when they encounter an angled corridor and the interaction occurs during that situation.

An angled corridor can be defined as a narrow hallway/passageway that connects a part of a building to another. It is encountered in all buildings, as it is one of the most important features of which it connects one part of the building to another. According to UBBL (1984), in case of piers or columns, a 2.25 m walkway is permissible for construction under certain requirements that will be elaborated further in the following subtopic. It is found that the walking velocity tend to be lower especially during turnings, and this can be explained by their psychological and physical responses that causes the pedestrians to slow down their walking velocity as they approach the angled corridor Dias et al. (2014).

2.2 Angled- corridor

Angled-corridor or corner may possess little to no significant differences. This is because both walkways share one common property, which is being constructed in a non-continuous manner. However, these two may be distinguishable in terms of angles incorporated during the designation of each walkway. Corner tends to have a distinct, clear-cut 90˚ angle, while angled corridors are not restricted to 90˚angle and are often associated to be constructed with varying angles.

Angled-corridors are located inside a building serve as an important location as it is the meeting point or the intersection point of two different corridors. Corridor can be defined as a narrow hallway/passageway that connects a part of a building to another. The intersections of the connecting corridors are places where people are most likely to congregate (gather into a crowd or mass). Figure 2.1 show some examples of corridor with long passageways in a building, usually seen with doors and rooms on one or both sides.

90° angled-corridor was the most significant angle that used in building structure. But due to the increment in technology complex geometries such as angled or circuitous walkways, which are common in places with high civilian bearing capacity, can significantly affect the microscopic walking characteristics of pedestrians. Understanding of bottleneck effects due to those complex geometries and capturing those in simulation model is crucial so that the analysis of pedestrians' walking behaviour can be conducted more precisely Dias et al. (2014).

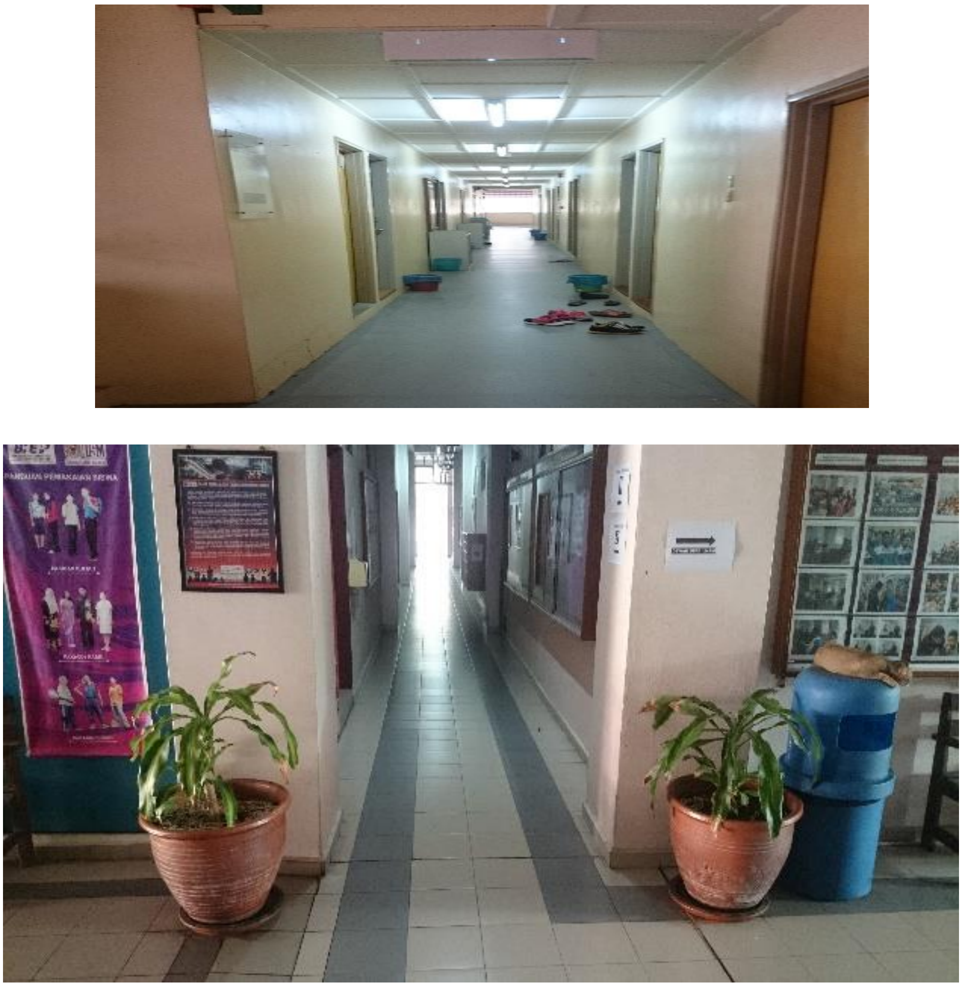


Figure 2.1: Examples of corridor with long passageways in a building, usually seen with doors and rooms on one or both sides. School of Civil Engineering and School of Materials and Minerals Resources Universiti Sains Malaysia (USM).

Angled-corridor are common geometrical condition that exists in most walkways of public facilities for serving pedestrians and can be encountered in all kinds of building. For instance, corners with right angle can generally be found in schools Guo and Tang (2012). In some cases, corners of other degrees can also be found, although it is less common than the right-angled corners. Nowadays, the design and layout of walkways corner has an even more complex design, and is often constructed with degree other than the conservative design of 90˚, and such designs are often seen in the construction of new buildings.

According to Dias et.al (2012), the turning angle of egress route is obviously one of the important features that must be designed properly. Angled or circuitous egress route and corridor are quite common, especially in public transport facilities, stadiums, and other public-gathering venues such as universities and schools. Therefore, proper considerations should be taken into account during the planning and designing stage of the escape area.

Malaysia has an established building code, namely the Uniform Building by Laws 1984, or in short UBBL 1984 that is enforced by the local authorities and applicable to all building types that is constructed within the local authorities areas. Referring to Uniform Building by Laws 1984, part III for space, light, and ventilation, there is a specification on the width of the footway that needs to be adhered to, of which the width of any veranda-way or uncovered shall not be less than 2.25 m, though in cases which involve piers or columns, veranda-way or footway that are of permissible to be constructed shall have a maximum depth of 600 mm from the boundary of the street.

2.3 Walking behavior

Each of human has their own unique behaviour, which advertently pose as markers to differentiate one distinctive human from the other. This includes walking behaviour, which can be defined as the walking pattern portrayed by an individual as he or she is traversing from one destination to another, Gorrini et al. (2013). Walking behaviour is often abstractive, as it may experience changes on the individual that subjected to variables that may affect the pattern or walking manner, whether it is from external source, internal source or even from both conditions.

2.3.1 Walking behavior related to angled-corridor

In recent years, researchers have shown interest in studying the reliability of pedestrian modelling and simulation tools that are used to simulate pedestrian walking behaviour associated with complex geometries such as angled-corridor. Several approaches have been recorded in literature to attempt the simulation of pedestrian dynamics associated with rounding corner or angled- corridor. The simplest approach is to locate the intermediate destination to change the desired direction and guide the movement through the desired path. For example, Steffen and Syefried (2009), Hocker et al. (2010), and Zeng et al. (2011) have considered one or several intermediate destination to plan the desired path beforehand. Chraibi et al. (2013) modelled each pedestrian direction around the corner through guiding lines and update rules based on occupancy of those guiding line by other pedestrians.

Through recent experiments conducted on a group of pedestrians, Dias et al. (2014) observed several behavioural characteristics that are specific to the walking action on angled-path. These can be summarized as, when negotiating a turn, individuals speed is reduced within a fixed region (say, “turning region”) that can be characterized with two points: namely turn initiation point and turn completion point. Moreover, there is a deceleration phase and an acceleration phase within this fixed region and the minimum speed occurs within the vicinity of the middle of corner. Percentage reduction in speed within the region is increased with the increase of turning angle and increasing desired speed.

Scanning is a subconscious process by which the pedestrian used to describe and observed the environment in order to avoid and step aside small obstruction on the floor. In addition, high degree of co-operation between pedestrian would be impossible argued by Dameen and Hoogendoom (2003). The pedestrian expect others to be cooperative in the conclusion of their walking task rather than obstructive on the walkways.

Due to ethical and safety concerns, it is impossible to collect any observations or empirical data by performing experiments with humans, especially when it comes to the simulation of panic situations. These issues have made it extremely difficult and challenging to model crowd dynamics, especially in complex situation under panic condition. However, several previous studies suggest that the collective behaviour of human and ants can be similar when they are escaping under panic.

To further confirm the above statement, Nishinari et al. (2006) mentioned that ants follow the preceding ants through pheromone trace, and pedestrians also try to follow others during evacuation in order to exit safely and efficiently. Thus, the use of data collected from the panicking ants as complementary data to analyse the behaviour of human under panic situation can be justified.

Empirical data with panicking ants and simulation result from Dias et al. (2012) show that the right angled egress path is 20% more ineffective compared with straight path of the same dimension. Thus, right angled egress path do cause in a decreased flow rate and increase in the escape time significantly compared with those straight egress paths.

2.3.2 Trajectories

Seitz et al. (2015) presented a concise movement model for pedestrians based on stepwise movement and they have done a series of controlled experiment to calibrate the model based on individual behaviour of pedestrians. The results show that a change of direction is constrained by the current walking speed because when the speed is higher, the smaller the probability for the pedestrians to change their walking direction. Based on the resulting trajectories, it is shown that the behaviour of pedestrians that has been found in the controlled experiment was, if there is adequate space, individuals will try to walk in the middle of the corridor. However, when congestion is present, multiple lanes are formed, thus allowing for a higher pedestrian flow.

The desired distance to the wall was kept while the pedestrians are walking around a corner. This behaviour is constantly portrayed as long as the situation did not require them to pass through a narrow environment. When that becomes the case, simulated pedestrian gave up the desire to a certain degree and took the most convenient path in the middle of the corridor. If the densities become higher, they further adjusted to the situation by forming multiple lanes in the corridor, a phenomenon that has been shown to occur in experiment as mentioned by Schadschneider and Seyfried (2011).

Empirical evidence indicates that although pedestrians frequently choose the shortest route, they are seldom aware that they are minimizing the distance as a primary strategy in route choice as stated by Hoogendoorn and Bovy (2004), Senevarante and Morall (1985). There is a higher probability that pedestrians tend to perform a biased and random walking action when they saw any opportunities of shortening their route distance and thus they often choose to traverse on the middle track. The movement of individual is affected by not only the surrounding obstacle and other pedestrians but also the route distance by Huang and Gou (2008). Q.zhang and han (2011), reported that the movement was influence by the others and some of interection might be helpful while so maybe impediment.

From the field experiments, it is found that since the density of pedestrian at the inner corner is higher than the surrounding areas, the inner corner is more often being used. In fact, from the studies conducted by Gou and Tang (2012), show that when pedestrians either move forward on the route in tangential direction or move into the route inside of those walkways from outside, their route distance to the destination will be shortened. Moreover, when a pedestrian walks around an angled corridor, the angled corridor wall will affect his or her movement and velocity. Besides that, the movement of pedestrian in the direction will be affected, and the angled corridor wall will impose a repulsive action on the pedestrian in that direction.

2.3.3 Walking velocity of pedestrian when facing non-straight walkways

Yanagisawa et al. (2009) experimentally demonstrated that walking speed is decreased when people makes a turn and this reduction in walking speed results in the decrease of pedestrian outflow. The reason of this, they pointed out was the effect of inertia. Influence of rotational inertia on turning locomotion has been discussed in detail by Eilam (1994), Carrier et al. (2001), and Lee et al. (2001) utilising experimental evidence from human as well as non-human test subjects. (Dias et al,exploring pedestrian walking through angled corridors, 2014) also stated that the deceleration increases with increasing speed and turning angle because the higher the approaching speed, the larger the work must be done to overcome the effect of inertia. Thus, the larger the work needed to change the working direction when it involved the larger turning angle.

Courtine and Schieppati (2003) verified that when the angled of deviation from the former direction increases, the mean body velocity decreases. They pointed out that on average, the velocity is significantly lower when walking along curved path when compared to straight paths under normal condition and one major reason for this is that they have established the disequilibrium of the body during the turning function.

As described by Ivanenko et al (2002), when the curvature of the walk way is larger, the walking speed tend to slow down and vice-versa, which can be mathematically described by the one-third power law i.e., the tangential walking speed is proportional to the one third root of the radius of the curvature of the path.

As established by previous studies, this reduction in velocity of individual pedestrian is due to psychological or physical responses that can create bottlenecks, when they collectively walk or escape as a group through circular or angled-path. This can be further clarified by the study conducted by Steffen and Seyfried (2009). With cellular automata model, they pointed out that sharp bend tend to move pedestrian to innermost lanes, thereby reducing the capacity of angled-corridor. Furthermore, they verified that right angled-corners in wide corridor could become bottlenecks, because the inner lanes are substantially blocked by outer pedestrian lanes at corners.

It is impossible to conduct experiment with human to reproduce panic situation due to ethical and safety concerns. Shiwakoti et al. (2011) and Dias et al. (2012) conducted several preliminary trial simulations with different turning angles and densities, and found that higher turning angles have significant impacts on pedestrian outflow, especially at high densities under panic conditions. Data collected through experimental studies with panicking ants can be utilised as complementary data to validate and verify the results obtained from such simulation study. Additionally, with proper calibrated and validated simulation tools, it is possible to study more complex scenarios and suggest evacuation strategies and design solution that can prevent or minimise crowd disasters.

Courtine and Schieppati (2003), experimentally demonstrate that an individual's walking speed is slower on a curved path than on a straight path. Moreover, study done by Segal et al. (2008) and Orendruff et al. (2006), they point out that, on average the magnitude of velocity when individuals walk on curved path is significantly lower than on straight path under normal walking condition and with or without vision. They established that one major reason for this result is the disequilibrium of the body, head, and limbs during the turning locomotion. Speed reduction as a result of limb asymmetry and body imbalance has been described in detail in their study.

The relationship between the curvature (inverse of the radius) of the path and the walking speed is centrally planned (i.e, by the central nervous system) and can be described mathematically with a linearly decreasing function on log-log space Hicheur et al. (2005), Vieilledent et al. (2001), Gribble and Ostry (1996), Ivanenko et al. (2002), and Olivier and Cretual (2007) (33-37). In other words, movements tend to slow down when the path curvature is high and speed up when it is low.

According to Hicheur and Berthoz (2005), human adapt locomotion pattern while considering the centrifugal acceleration when walking on curved path. As the authors have verified, a reduced speed provides the body with a more stable frame to steer along the curved path. Reducing one's speed along curved paths also can minimize asymmetry and unbalance in tank, limbs, and head (Hicheur et al. 2005 and Imai et al. 2001). Therefore, a reduce speed on curved path allow pedestrian to negotiate the curve smoothly and efficiently.

Experiments done by Dias et al. (2014) indicated that there is a clearly observable deceleration effect when an individual walks along an angled path. It was observed that this deceleration increases with increasing speed and turning angled, because the higher the approaching speed, the larger the work that must be done to overcome the effect of inertia. Similarly, the larger the turning angle the larger the work that must be done to change the walking direction.

Effects of turning movement on pedestrian movement for normal and orderly evacuation have been studied by several researchers. Yanagisawa et al. (2009) pointed out that the speed of escaping pedestrian is decreased when they turn because of inertia and this results in the decrease in outflow. The experiment was performed on humans as test subjects under normal condition showed that pedestrian outflow decrease when the pedestrian needed to change their orientation at the exit.

Courtine and Schieppati (2003), empirically verified that when the angle of deviation from the former direction increases, the mean body velocity decreases. They pointed out that on average, the velocity was significantly slower (about 1%) when people walk along a curve compared to when they walk on straight path, both with and without vision under normal condition. Furthermore, they experimentally establish that for turning velocity of or about 1 m/s, trunk roll increase when a change in heading direction increases.

Furthermore, this disequilibrium of body results in severe consequences where people fall, they get trampled and crushed by others, particularly under panic condition. This phenomenon can be further verified by observing the real-world data of an in-store stampede as examined by Shiwakoti et al. (2011).

2.4 Phenomena at angled-corridor

2.4.1 Congestion

Collective egress during emergencies such as natural disasters or terrorist attacks of which rapid egress is essential for escape. Studies conducted by Shiwakoti et al. (2011), the important aspect of collective egress under emergency condition is the turning movement when a sudden change in direction or the layout of the escape area occurs. They examined the consequences of the turning movement through an experiment with ants and real-life data, and also performed a simulation to simulate the crowd of pedestrian at angled escape routes.

Zhang et al. (2012) said that the dynamic of pedestrian streams is complex around the angled-corridor. This can be supported by Dias et al. (2012) the effect of turning angle is further pronounce when the density is increase. This is due to the presence of stronger conflict, interaction, and pushing behaviour in turning scenarios such as many escapees try to escape at the same time.

From the simulation results Shiwakoti et al. (2011), it was found that the collective movement was uniform in nature when pedestrians pass through the straight corridor. In contrast, congestion was observed at the turning junction and creating a delay in egress when pedestrians pass through the angled-corridor as shown in Error! eference source not found.. They concluded that the straight corridor (turning angle of 0°) is the most effective in term of flow compared to other turning angles because the flow rate in cases of 45°, 60°, and 90° turn was decreased when compared to straight corridor.

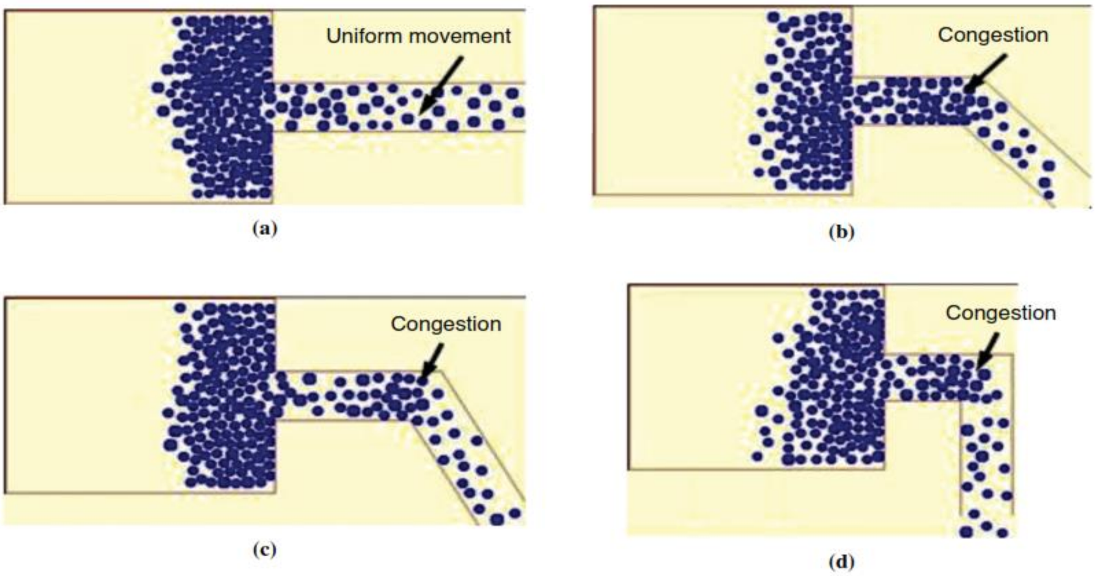


Figure 2.2: Snapshots of simulation for pedestrians escaping through corridors with different angles: (a) straight corridor, (b) 45° corridor, (c) 60° corridor, and (d) 90° corridor

2.5 Interaction between walking pedestrian

The interaction force include the attraction and repulsion effect. The attraction effect are formulated to prevent the separation between two person element in the same group. While the repulsion effect are to avoid overlap between person element in the same group Rahman and Gotoh (2015). This is an important element that needs to be taken into consideration especially to determine the best solution for every scenario that might occur due to the variation of pedestrian density and effective angled of corner corridor.

According to Graat et al. (1999), when people are walking on walkways that are increasingly crowded, people tend to keep some comfortable space between themselves and the others by slowing down their walking speed. This is understandable since even though people wanted to evacuate as swiftly as they can, they also wanted to be able to evacuate safely. This can be achieved by lessening any unnecessary body contact with others.

With regards to repulsion effects, according to Helbing et al. (2001), people can only move freely under less dense crowd, their movement and motion will be influenced by repulsive effects with other people which gave rise to self-organization phenomena. Similar to Lakoba et al. (2005), on a book named Simulation, stated that when the crowd density had increased considerably until it forces people to collide with each other, physical forces such as repulsive effects started to interrupt the flow of motion.

Gotoh et al. (2012), have investigated computationally about the mechanics of sediment transport by using 2D and 3D granular material model based on Distinct Element Method (DEM). The perception domain for self-evasive action for avoidance force acts on pedestrian in positive case and negative case of the moving direction-component of the relative velocity vector between the pedestrians. Whereas, the perception domain, in which both the physical repulsive force and psychological repulsive force acts on each individual pedestrian. Noted that the physical repulsive force acts between pedestrian and wall, meanwhile, the psychological repulsive force act only between pedestrian.

Gorini et al. (2013), the time for egress and evacuation is influenced by the present of group. Group are define as two or more people who interact to achieve a share goal. They move as block formation within the crowd with an order of evacuation that other pedestrian cannot evade. Moussaid et al. (2011), the physical interaction between bodies may occur. Thus the intentional avoidance behaviour of pedestrians adapting their motion according to perceived visual cues and unintentional movement may result from interaction forces by collision with other bodies.

The interaction force acting on each pedestrian is a significant output from the current trial simulations. The measurement investigation for injury on human has been previously reported. An experiment investigation on the maximum endurable force during earthquake evacuation had been conducted by Langston et al. (2006). They found that the maximum interaction force of 162 N and 242 N for a fit young female (60 kg) and a middle-aged male (74 kg) respectively. Another study was conducted by Smith and Lim (1995) on the level of comfortable loads for pedestrian. Twenty-one pedestrian with range of age from 20 to 25 years old had been tested on three barrier types loaded on upper and lower chest and abdomen. They find that the comfortable limit of loads ranged from 175 N to 247 N. Hence, the range of the comfortable loads used in this work as a benchmark for the safe level of interaction forces for each pedestrian were 162 N and 242 N since it is found from the most recent studies.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter mainly describes the procedures implemented for data collection as well as the methodology deployed in achieving the objectives of study. Also, briefs on the study background and analysis procedures are being included. There are two main parts involved in this study, which are the experimental works and simulation work.

In experimental work, there is three vital components being investigated, which are pedestrians' distribution, trajectories of pedestrian walking, and velocity of walking pedestrian. This is achieved by establishing three walking tracks for each angled-corridor of 60°, 90°, and 135°. The pedestrian are requested to perform their walking action and the video footages were recorded during the experiment in order to determine the trajectories and velocity of each pedestrian.

In order to determine the trajectories of the pedestrians, Autodesk® MAYA® 2016 (MAYA) software, Human Behaviour Simulator (HBS) tool, and Crowd Behaviour Simulator (CBS-DE) simulator were used. Based on the finding, it is observed that upon reaching the angled corridor, most pedestrian tent to moved inwardly closing in toward the corner. As for the velocity of participant, the analysis was conducted to investigate the relationship between the number of pedestrian (NOP) and the average velocity recorded for single pedestrian and group of pedestrians.

Meanwhile, in simulation works, there are four issues investigated of which includes the number of escaped pedestrian (NEP), inflexion point, scenario of egress time, and the repulsion effect. Five simulations have been performed, each incorporating 60, 70, 80, 90, and 100 number of pedestrian respectively, as they were walk on three designated angled-corridors of 60°, 90°, and 135°.

In order to justify the result obtained on egress time, there are two important aspects to investigation. First, the determination of inflexion point. Reduction in pedestrian's velocity can be further analysed by observing the existence of inflexion points. Inflexion points are also used in the determination of threshold density as well as to locate or indicate the occurrence of congestion during simulation. The second aspect of interest is the effect of repulsion which is also worth noting for as it does pose an effect towards the average velocity, egress time, and safety aspect.

Figure 3.1 portrays the schematic flow of study procedures to achieve study objectives. The study activities are divided into two parts which are experimental part, and simulation part.

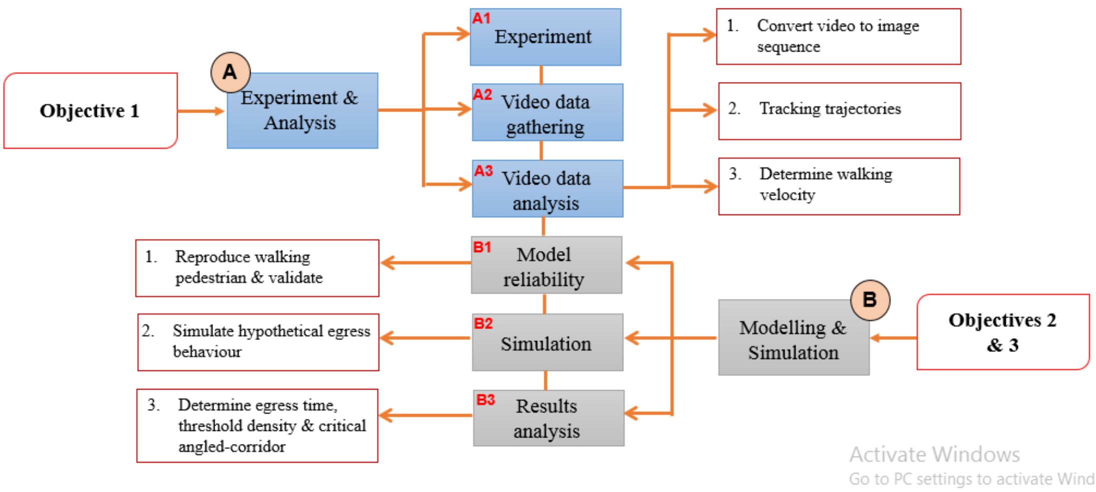


Figure 3.1: The schematics flow of study procedure

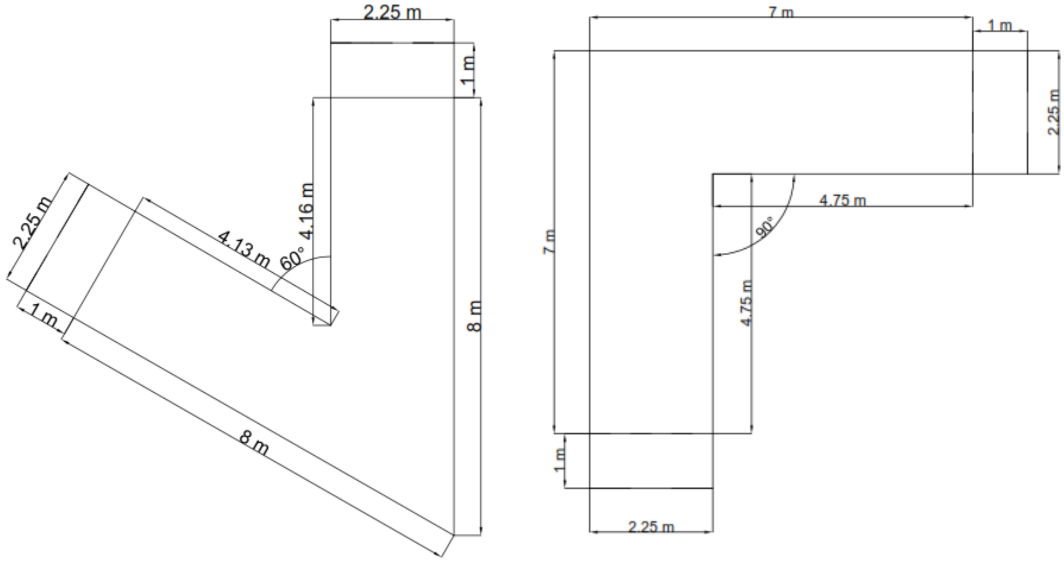
3.2 Experimental Work

3.2.1 Experimental Setup

The three different degrees of angled-corridor were set –up following the schematic diagram as shown in Figure 3.2 (a), (b), and (c). the specification of the angled-corridor were based on the comparison between normal angle (90), acute angle (<90), and obtuse angle (>90). Figure 3.3 (a), (b), and (c) shows the layout of three different angled-corridor that have been set-up at Dewan Serbaguna, Engineering Campus, Universiti Sains Malaysia on the 5^{th} and 6^{th} November 2016. The angled-corridor were built by using stand board. Red scotch tape was placed on the floor to mark both starting and ending points. Two waiting rooms have been provided at the ends of the built-corridor. Pedestrians were represented by the students from Engineering Campus, Universiti Sains Malaysia, comprising of 60 student in a mix gender. The distribution of pedestrians gender were not taken as an important factor in this study.

All the pedestrians had given a task to walk through the angled-corridor for uni-directional flow. Each of the participant were provided with coloured cap (red or blue) and white T-shirt. The red and blue cap used to differentiate the participant numbering which is the red cap represent number 1-30 while for the blue cap for number 31-60. Both cap and T-shirt were used to be sure of a sufficient contras between the pedestrians and the background.

The inflow rate for this experiment were according to the normal walking situation for all run with different set number of pedestrian (NOP = 1, 15, 30, 45, and 60). Prior to the commencement of the experiment, pedestrian were requested to stay in waiting room at the end of the angled-corridor. Noted that the task were done according to the angles designated which are 60°, 90°, and 135°.



(a) (b)