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Author(s): Muammer Yaman

Affiliation: Gazi University, Ankara, Turkey

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Effect of Exit Door Width on Flow Rate in Occupant-based Fire Evacuation Scenarios in Dormitories

Muammer Yaman*

Gazi University, Ankara, Turkey

Abstract

Student dormitories are intensely used buildings that meet the resting, accommodation and living needs of students. It is necessary to ensure the safety of students and to eliminate possible risks in dormitories as intensive use areas. Fires pose a great risk in dormitories and may cause serious casualties and injuries. The reduction of casualties and injuries can be achieved by analyzing occupant behaviour during fires according to the building use scenarios. In this paper, a type of dormitory that provides two alternative exits is explored. The building use scenarios of the dormitory were investigated by making on-site observations. Students' use of sleeping units, dining units and partial sleeping/dining units and fire exit routes were determined. Pathfinder computer program was used to analyze the fire evacuation performance. This program was defined in accordance with occupant behaviour and different fire evacuation times were suggested depending on the building use scenarios. At the end of the study, based on the evacuation times, the flow rate at the exit doors according to the location of the occupants was analyzed. In the fire escape routes, as the upper floors are reached from the lower floors, the occupant flow rate decreases at the exit doors and the flow rates continue to be stable as the number of occupants is saturated according to the door width. The decrease in the number of occupants in the dining unit decreases the flow rate at the exit doors. It is important that various assembly units in dormitories, such as the dining unit, are designed on floors that can directly provide evacuation to a safe area. The results obtained are suitable for all dormitories, residences, hotels and other similar buildings.

***Keywords*:** building use scenario, dormitory, evacuation, flow rate, exit widths

*Corresponding Author: muammeryaman@gazi.edu.tr

Introduction

Student dormitories are accommodation and residentialbuildings where students meet their learning, living, and resting needs. As the future of countries, students should be able to live their life to the fullest with ease and comfort. For it to be possible, their accommodations should reflect their needs and ensure their safety. The presence of wooden tables, desks, beds, books, and study units greatly increases the risk ofa fire loadin the dormitories. Moreover, theintensive use of crowded indoorspaces in these dormitories poses a great risk in case of afire. When students' are asleep in these spaces and a fire breaks out, itwill take them longer to sense its presence. Thus, crowded sleeping units and delayed reaction to the fire (pre-evacuation time) increase the safety hazards in dormitories.

Many student dormitorieshave caught fire in countries all over the world due to inadequate fire safety measures.The United States of America has been one of the leading countries which hasprepared and publishedfire statistics around the world. The statistics reveal the importance of the subject and the necessity of both active and passive fire safety precautions that can be taken to prevent fires in dormitories.According to the report prepared by the National Fire Protection Association (NFPA), approximately 4.100 fires occurred in dormitories, fraternities, sororities, and barracks between 2011-2015. It was also reported that 35 people were injured in these fires. Statistical evaluations for the same time period provided within the reportthat the main cause of student dormitory fires was the presence of cooking equipment, it caused 87% of dormitory fires. The remaining 5% of student dormitory fires were intentionally set fires, 3% were smoking material fires, 2% were heating equipment fires, and the remaining2% were electrical distribution and lighting equipment fires (Campbell, 2017). In the recent past (2016),11 students and 1 officer died in a dormitory fire that occurred in Adana, Turkey. According to the report of the commission written after the fire, it was stated that one of the fire doors was made of PVC, and the other fire door did not have a door handle and was not opened during the evacuation.Additionally, keeping exits locked and unused for security purposes also poses a great riskin the dormitories in case of a fire. It is recommended that dormitory staff and employees should be aware ofalternative solutions, such as fire codes and drills,so that they may control the injuries and destruction caused by a fire.

In the case of a fire,the loss of life and property can be reduced by adopting fire safety designs (active and passive fire safety precautions) (Yaman, 2020).In the study conducted by Tian et al., it was concluded thatuniversity students' knowledge about fire hazards was inadequate, and students could not determine the most appropriate escape route during a fire (Tian et al., 2012). In the study conducted by Meng et al. (2016), it was found that university students' knowledge and behaviourduring fire was wanting (Meng et al., 2016). In the study conducted by Zakaria et al., detailed scoring of fire safety precautions in student dormitory buildings was examined on four basic systems including: fire safety awareness level (71.01%), fire safety knowledge level (68.42%), visual inspection of the fire safety protection system (82.79%) and emergency response plan document examination (70.37%).It was recommended that fire safety awareness should be raisedso that the occupants are acquainted with the necessary safetyprecautions (Zakaria et al., 2019). In recent years, along with the occupant and fire awareness studies, checklists werealso prepared as a practical control method against fires. Currently, checklists for student dormitories in the design phase areavailable and are highly preferred (Sanni-Anibire et al., 2015; Arghami et al., 2016; Center for Campus Fire Safety, 2021). The basic principle of fire safety suggests the use of fire safety designsto create appropriate evacuation conditions according to the building usescenarios, and to raise an occupant's perceptual and behavioural awareness occupants about fire hazards.

Although many countries have designed and imposedfire regulation requirements (access to the safe area of the occupant), manydifferences have been observed in building evacuation times. According to previous studies, it is important to analyse the evacuation risks associated with a building by constructing occupant-based evacuation scenarios (Hadjisophocleous & Bénichou, 2000). Building use scenarios that arise from different uses of a building should be determined and applieddduringfire evacuation drills. For this reason, studies suggest that it is important to create performance-based fire evacuation scenarios and develop project-specific fire safety precautions (Yung, 2008). Performance-based fire safety precautionsinclude minimizing the loss of life, eliminating potential fire risks, reducing property and economic losses, and limiting fire spread (Takeichi et al, 2003; Chixiang et al., 2012).

In this study, an evacuation designbased on theperformance-based fire safety precautions in student dormitories wasinvestigated, and fire escapes asa life safety measurewere analysed. According to the building use scenarios, the effects of the exit door's width on flow rates during a fire evacuation were investigated. Additionally, according to the different locations of the occupants,the overcrowdingat the exits wasalso evaluated. This evaluation was used to determine and explain the increased/decreased flow rate during the total time of evacuation.

Material and Methods

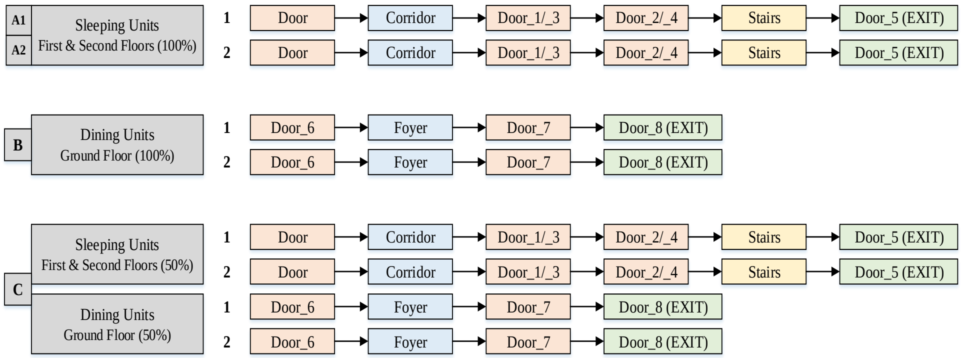
In thispaper, a dormitory of students at the post-secondary level was takenas a casestudy. The student dormitory represents a typical college dormitory building with a basement floor, ground floor,and 2 other floors (sleeping units). The vertical circulation of this dormitory consists of two fireproofing stairs, two circulation stairs (open stair), and a common circulation elevator.

For thisstudy, the locations of the occupants (students) were determined through on-site observation and building use scenarios. To define possible evacuation risks in building use scenarios, research was conducted to limit the values so they stay within the parameters of the safe zone. As a result of on-site observations, the building use scenarios of the students were divided into 4 scenarios.In scenario A1, all studentswere in the sleeping units (at night, A1).In scenario A2, all studentswere working/studying in sleeping units (working status, A2).In scenario B, all studentswere in the dining unit (at dinner, B).In scenario C, it was established that half of them were in the sleeping units and half were in the dining unit (in the evening, C). Two different exit alternatives for each building use scenario were presented.

The building use scenarios and escape route designs were investigated (Fig. 1). As a result of on-site observations, it was determined that the dormitory's basement floor did not have a decisive/dominant role in the fire evacuation scenario. Therefore, basement uses were excluded from the scope of assessment in building use scenarios.

Figure 1

Building use Scenarios and Exits in Student Dormitory Buildings

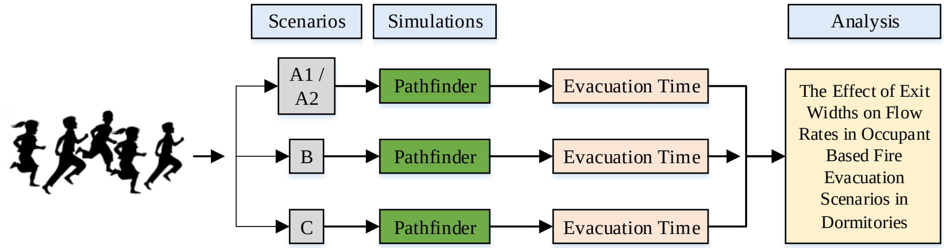


Building use scenarios and fire evacuation phases created within the scope of the study were analyzed with computer simulation methods. Pathfinder, developed by Thunderhead Engineering and created with anoccupant-based motion/partial behaviour model, was used to simulate scenarios (Pathfinder, 2012, 2017). Pathfinder provides two ways to model the evacuation process, namely SFPE mode and Steering mode. The SFPE mode implements the concepts in the SFPE Fire Protection Engineering manual. Although this mode is known as the flow model, it is based on the calculation of exit capacities (DiNenno et al., 2012). Steering refers to the reactive and unintentional actions of physical users (Nareyek et al., 2003). By using these movements, Reynolds defined a hierarchical model responsible for determining the path of individual characters in animations and games (Reynolds, 1999). With this definition, Amor et al., explored the concepts of congestion and queuing in the occupantbehaviour process. This model explains that the occupants move along their intended paths while interacting with the environment and other residents. In this method, occupants determine their pathsby usingthe shortest distance route. Entry data related to the delay time is determined by distribution rules, walking speed, and body measurements of the occupants. Just avoiding collisions is important when evaluating occupant behaviour (Amor et al., 2003).

Within the scope of this study, student dormitories, depending on the building use scenarios, were analyzed through the Pathfinder computer program. In the designed evacuation systems, the flow rates were analyzed depending on the width of the escape route (doors) (Fig. 2). In this case study, post-secondary education dormitories were examined to evaluate the evacuation times in case of a fire. Recommendations were also given using the results as conclusive evidence.

Figure 2

Conceptual Framework of the Study



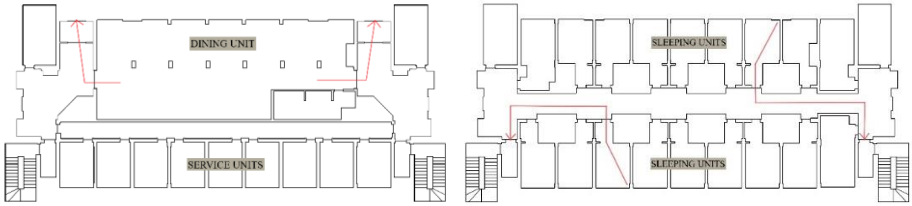
Case Study and Simulation

Based on the use scenarios of the student dormitories, the evacuations were analyzed in the Pathfinder computer simulation program. The student dormitory, which was the sample for this study, consisted of standard sleeping units with 4-person rooms.Each room had its own wet areas. The dormitory was investigated as a building on the ground floorwas analysed over different building use scenarios (Figure 3). According to the building use class, theoccupant load of the dormitory used in the study was calculated in accordance withTurkey's Regulation on Fire Protection, TRFP (forstudent's bedroom 10 m^2/person or 4-person rooms) (TRFP, 2015).

The student dormitory floor plans were modelled in three dimensions and then wereexported to the Pathfinder simulation program. The rooms (spaces) and exitswere defined in the simulation program. Studentbased uses were accepted in occupant definitions of the program. Within the scope of the evacuation simulation program, the free movement speed (constant speed, unless there are obstacles and other users nearby) was accepted as approximately 0.73 m/s for students aged 18-22. In this case, the students' speedwas defined in the range of 0.6–0.8 m/s in occupant definitions. The average speed for occupants (adults) in various service units on the ground floor of the dormitory building was accepted as 1.19 m/s default settings in the software In building use scenarios, the pre-evacuation time at night time was definedas30s (sleep status) (Lei et al., 2012a; Lei et al., 2012b).

Figure 3

Case Study Ground Floor (A), 1. and 2. Floors(B) Plan



(a) (b)

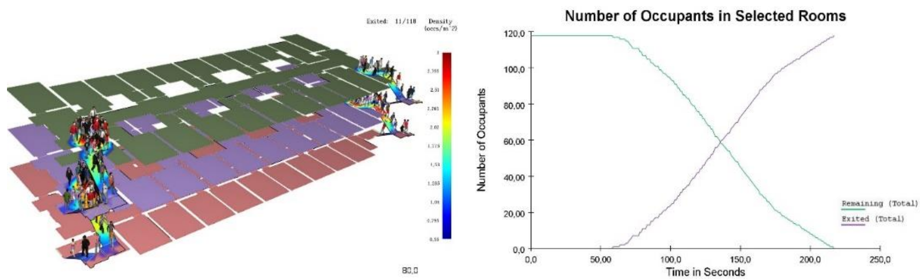
Students in Sleeping Units

Sleeping, studying, and resting times are mostly spent in sleeping units of student dormitories. The increase in the number of students staying in sleeping units makes fire evacuation difficult. In the study conducted by Corrêa et al., a large-scale experimental fire investigation was conducted in a designated sleeping unit. In this study, shortly after the combustion of the combustible material (the start of the fire, temperature), the temperatures at the eight measuring points of the rigs in the centre of the dormitory unit increased rapidly. In the first 3 minutes and 40 seconds, the thermocouple, 2.4 m from the ground, recorded a temperature of 600 °C. The formation of a dense and saturated cloud of exhaustgas caused an increase in the internal pressure (more than outside), preventing the atmospheric air and thus oxygen to enter indoors. The highest indoor temperature (675 °C) was detected in the first 8 minutes and 35 seconds (Corrêa et al., 2018). In an experimental study by Tabaczenski et al., software Fire Dynamics Simulator (FDS) was used to carry out a numerical simulation, which concludedthat the experimental studies found similar results assimulation studies (Tabaczenski et al., 2018). The results of this study determined that the sleeping unit has a high fire load, and in case of a fire, the temperature would rise rapidly, while the oxygen levelin the air would decrease exponentially.Thus, it is important to providea rapid evacuation systemto students in case of a fire. To craft such a system, evacuation time needs to be calculated depending on varied sleep scenarios.

In thiscase study, it was observed that the students used thesleeping units when theyneeded sleep A1 (night) or when they needed to study A2 (working). An evacuation simulation study was conducted for the above-stated scenarios separately. A total of 118 students defined in the dormitory sections were investigated during the fire evacuation study. In the simulation, evacuation time was determined to be 3 m 36 s (216 s) in scenario A1 (Fig. 4), and in scenario A2, the evacuation time was determined to be 3 minutes 6 s (186 s).

Figure 4

Fire evacuation phase (11 occupants/80 s) in scenario A1 (a), evacuation time, and the number of occupants evacuated depending on the duration in scenario A1 (b)



(a) (b)

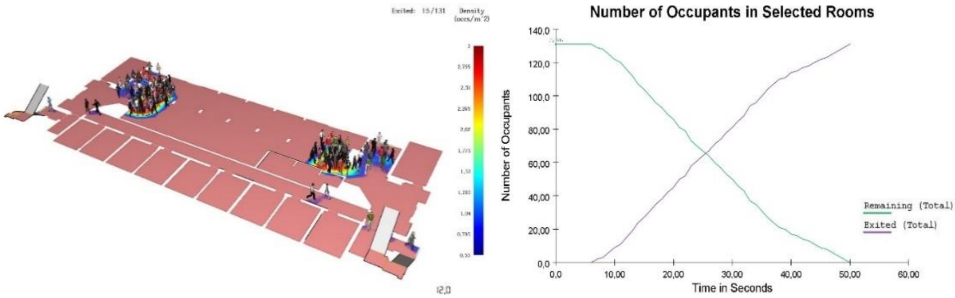
Students in Dining Unit

In this experiment, there was a dining unit situated in the dormitories to meet the eating needs of the students. In the dining unit, kitchens, and stores were referred to assub-service areas. Generally, the presence of a kitchen in abuilding causes heat to build up. Itsstores act as fuel in the fire triangle (heat-fuel-air) and pose a significant fire hazard thatincreases the spread of fire (Razon, 2017). When the reasons behind dormitory, fraternity, sorority, and barracks fires were examined by the fire statistics of NFPA 2011-15, it was determined that 87% of the fires were caused by cooking equipment (Campbell, 2017). Thus, the dining units pose a great risk since they can cause fires to emerge in the kitchen sections. It is deduced that students in the dining units should be evacuated as soon as possible in case of a fire.

In thiscase study, the B (dinner time) fire evacuation scenario for the dining unit planned on the ground floor was examined. In scenario B, the occupants in the service units on the ground floor werealso included (building fire evacuation appropriate for current use). In Scenario B, students and the other users (131 occupants) were evacuated from the building in 50s (Figure 5).

Figure 5

Fire evacuation phase (15 occupants/12 s) in scenario B (a), evacuation time, and the number of occupants evacuated depending on the duration in scenario B (b)



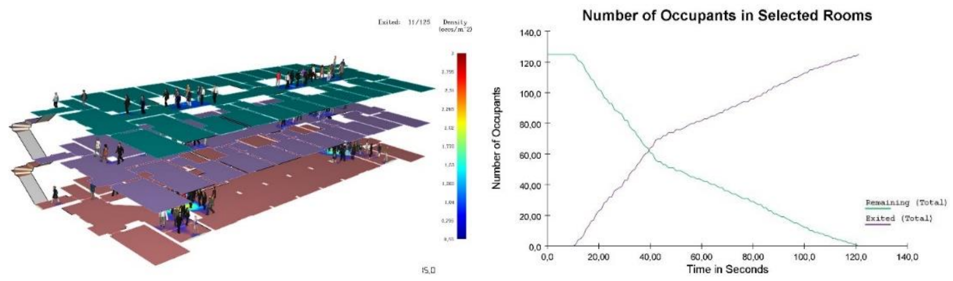
(a) (b)

Students in Sleeping and Dining Units

With scenarios A1, A2, and B, a partial distribution of the students in the dormitories was observed.The students were distributed in half between the sleeping and dining units.In Scenario C, after the evacuation, the students were aware andconscious. In scenario C, the students and the other users (125 occupants) were evacuated from the building in 2m 1s (121 s) (Figure 6).

Figure 6

Fire evacuation phase (11 occupants/15 s) in scenario C (a), evacuation time, and the number of occupants evacuated depending on the duration in scenario C (b)



(a) (b)

Results

Depending on the building use scenarios, evacuation took place in the student dormitories at different times. Within the scope of thiscase study, evacuation times were determined depending on the building use scenarios. Evacuation timewascalculated to be 216 s in Scenario A1,186 s in Scenario A2,50 s in Scenario B, and 121 s in Scenario C in the computer simulation program. During the evacuation phase, when the occupants passed through a narrowing exit (bottleneck) on the escape route, overcrowding at the narrow exitscaused the evacuation time to be longer.

In scenarios A1 and A2, students' evacuationfromthe 1stand 2ndfloors wasevaluated. The students hadtwo exitoptions from theirsleeping units. Additionally, the overcrowding at the exit doors in the fireproofing stair evacuationwasanalysed. The difference inscenarios A1 and A2 was that in the case of A1, the students were in sleep status. In scenarioA1, the sleeping unit's doors had cleanwidths of 85 cm, and the fireproofing stair doors had widths of 100 cm. The doors of the sleeping units were excluded from the evaluation since the in-room occupant density was low and occupant-based pre-evacuation times wouldgive varied results. It was found that the overcrowdingat the exits, defined as Door_1 and Door_2 for scenario A1,was created by the 1st floor occupants. Consequently, the flow rate at theseexits increased above 0.6 pers/s, and with it, the occupant speed decreased steadily (completed within 91 s). Furthermore, at the exits defined as Door_3 and Door_4, overcrowding was observed due to the 1st and 2nd floor's occupants. Initially, the flow rate at the exits wasabove 0.6 pers/s,but it decreased slowly due to overcrowding at the exits, andafterwards, it remained constant.By the time evacuation was completed, the flowrate was decreased again (completed within 112 s).It should be noted that for the first 66 seconds, the occupant evacuation time for the last exit, defined as Door_5, was not considered as a part of the evaluation(Figure 7).

In scenario B, the students werein the dining unit that was located on the ground floor. They were evacuated directly to the safe area (outdoor environment) without using the fireproofing stairs. There were twoexit optionsin the dining unit. The door opening from the dining hall to the entrance hall, the windbreak door, and the last exit door hada clean width of 170 cm with double wings. For scenario B, 1.67 pers/s flow rate was reached within 15 s at the exit defined as Door_6. The large door width increased the flow rate. An equivalent flow rate was determined in the exits (consecutive exits-buffer zone) defined as Door_7 and Door_8 (last exit). The highest flow rate of 2.01 pers/s was detected in the first 40 s. The occupants actively used the exits during evacuation; the flow rates remained constant for a certain period of time and were not reset (Fig. 8). The presence of double-wing doors in the dining unit increased the exit widths, and thus increased the flow rates as well. Additionally, the dining unit's planning on the ground floor facilitated occupant evacuation directly to the safe zone.

Figure 7

Flow Rates at Exit Doors in A1 Scenario of Fire Evacuation

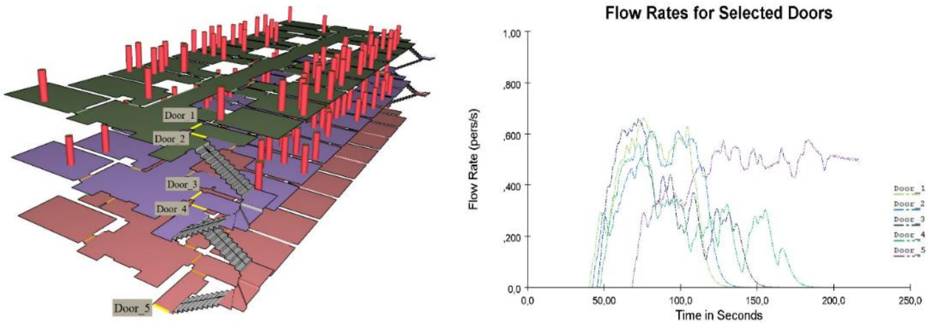
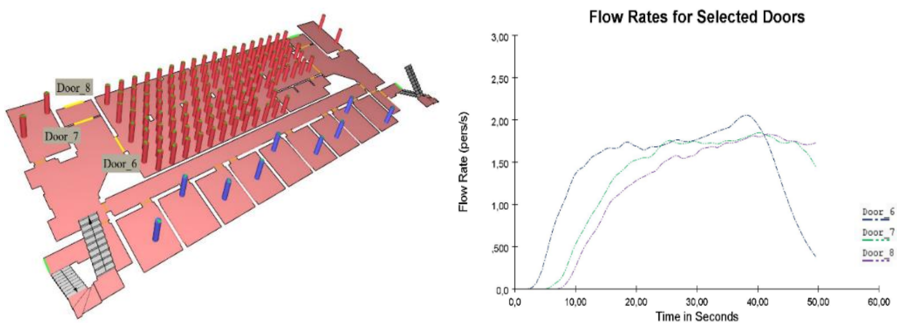


Figure 8

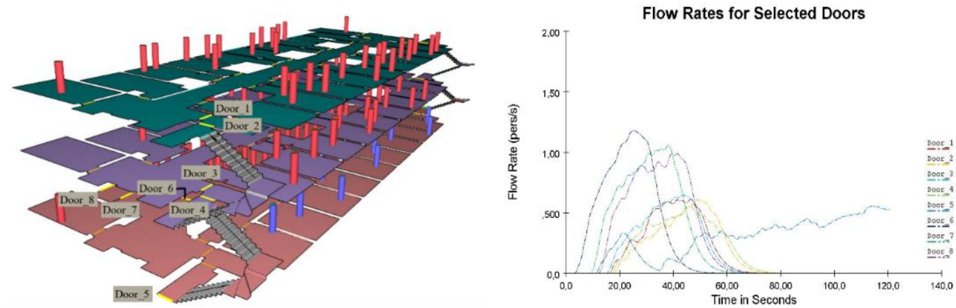
Flow Rates at Exit doors in B Scenario Fire Evacuation



In scenario C, an evacuation scenario was planned based on a uniform occupant distribution in the dormitories. Half of the students were located in the dining unit and half in the sleeping units. Students in sleeping units were defined as being conscious and able to act directly during a fire. Flow rate at Door_1 and Door_2 exits was determined to be 0.6 pers/s. It should be noted that the number of students on the 1st and 2nd floors was less than the students on the 1st and 2nd floorsinscenarios A1 and A2. This difference prevented overcrowdingthat occurred at the Door_3 and Door_4 exits. The flow rate at Door_3 and Door_4 exits reached the highest at 0.6 pers/s levels as compared to Door_1 and Door_2 exits. The flow rate at Door_6 and Door_7 reached a lower flow rate when all students had reached thedining unit (Scenario B). The flow rate at Door_6 and Door_7 was the highest at 1.18 pers/s. Furthermore, due to the low number of evacuated occupants, Door_6, Door_7, and Door_8 were not actively used during the evacuation and the flow rates were reset at the exits depending on the escape route (Figure 9).

Figure 9

Flow Rates at Exit Doors in C Scenario Fire Evacuation



Discussion

Studies reveal that fire evacuation spaces in student dormitories should be designed according to building use scenarios. Furthermore, the presence of occupantsin different locations at different periods of the day having a varied state of consciousness makes it necessary to create differentbuilding use scenarios that could be utilized to design fire evacuation spaces. Depending on the locations of the students, it is also necessary to find outand evaluate flow rates of the escape routes having exit doors with varying widths. In this case study, it was observed that students were partiallypresent in the sleeping and dining units.In both units in the dormitories, the effect of exit door's widthon the flow rates was evaluated.

In scenariosA1 and A2, overcrowding was observed at the exit doors located in the sleeping units, especially on the stairs where the upper floors meet the lower floors. While the flow rates at Door_1 and Door_2 exits remained constant at one level, the flow rate graph at Door_3 and Door_4 showed a gradual decrease after being constant at two levels. At Door_5 exit, duringthe evacuation from the nearest floor, the flow rate graph increased depending on the concentration of the occupants. The graph's elevation line was stable and remained constantuntil the end of the evacuation. Thus, it was determined that as occupants approach the exits, flow rates increase when the floor'soccupants increase.

In Scenario B, the fact that the dining unit was located on the ground floor played an important role in the direct evacuation of students to the outdoor environment. The width of the doors used in the evacuation phases of the dining unit was more than the width of the fire escape doors, and Door_6, Door_7 and Door_8 had the highest flow rate values. The doubling of door widths in scenariosA1-A2andof the dining unit doors in scenario B was beneficial since theirflow rate wasthree times that of the same occupant load.The fact that all students werein the same enclosed space and hadquickaccess to the exits supports this deduction. In this case, it is very important in terms of fire safety that the assembly units (dining hall, conference hall, library, etc.) as intensive use areas in student dormitories are designed in the ground floor planning.The exit widths should be keptlarge becausebeing on the upper floors increases the evacuation times rapidly due to overcrowding.

In scenario C, the flow rates of the students in the sleeping units and the dining unit wereconstant depending on the decrease of the occupants at Door_1, Door_2 Door_3, and Door_4. Number of students decreased depending on scenario A, 0.6 pers/s flow rate was determined. The flow rate at Door_6, Door_7, and Door_8 was the highest at 1.18 pers/s. Thus, it was deduced that the decrease in the number of occupants in the dining unit and the presence of large exit door widths increases the flow rate.

Conclusion

It was determined that in student dormitories, different building use scenarios have varied evacuation times, which results indifferent flow rates at exit doors. In the fire escapes, as the upper floors werereached from the lower floors, the occupant flow rates decreased at the exit doors.The decline in the flowrate was stable as more students reached the exit doors with narrow widths.This situation caused the total evacuation time to increase significantly. Thus, it is suggested that the width of the exit doors should be increased the closer they are to thelast exit (bottleneck blocking). This can be used as an alternative solution to prevent possible overcrowding at exit doors. Additionally, the decrease in the number of occupants in the dining unit (assembly units) in different building use scenarios caused a decrease in the flow rates at the doors. Each occupant's access time to the door was prolonged, which reduced the number of students passing through the door per unit per second. The fact that the dining unit wasdesignedon the ground floor plan (direct access to the safe area) and haddoublewing doors was determined to bean important design parameter for fire evacuation spaces. It should be kept in mind that the research was conducted in a computer simulation program, and evacuation times and flow rates were adapted depending on the occupant behaviour analysis of real uses/situations. The results obtained from the paper are applicable on all dormitories, residences, hotels and etc. It is suggested that future researchers should examine the evacuation times of the dormitories with a larger number of students/occupants. They should also investigate the flow rates of different escape routes.

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