# Experimental Studies on Wheelchair Passing Through Fire Doors

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## ABSTRACT

The purpose of the study is to investigate the criterion for the force required to open fire doors, and the required dimensions of fire door frames, from an ergonomic point of view for wheelchair users, through conducting experimental studies on passing through fire doors.

This study implemented two types of experimental design, observing subjects passing through fire doors, and measuring the force required to open them.

The results of the study show that it is desirable for fire doors to have a required opening force of no more than 40N and a width of more than 850mm. When using a wheelchair, the direction from which the door is approached has a significant impact on whether or not the subject can pass through the door. From these observations, it is postulated that in cases where corridors are narrow and there is not sufficient room to maneuver a wheelchair, a wheelchair user will often be unable to evacuate safely to the stairwell if they approach the fire door from the door knob side. Therefore it is essential that there is sufficient space in front of the fire door to bring a wheelchair parallel to the door, and also to rotate the wheelchair 180 degrees when necessary.

**keywords:** Human behaviour, Wheelchair, Fire door, Evacuation

## 1. INTRODUCTION

In recent years construction allowing easy access to buildings is increasing in Japan following the enactment of the Law for Buildings Accessible to and Usable by the Elderly and Physically Disabled People (commonly known as the Heartful Building Law) to encourage access to buildings for senior citizens and disabled people. However, these regulations refer to access in daily life, and do not make much reference to barrier-free evacuation in emergency situations. When evacuating from high-rise buildings, it is imperative to reach the ground as soon as possible. However, for wheelchair users with limited mobility, heavy fire doors and stairs present an obstacle. Because it is difficult for disabled people to move between floors without help in an emergency situation, they need to at least be able to make their way to a safely partitioned stairwell. However, the criterion have yet to be established regarding the strength needed to open and close fire doors in emergency situations, and there is little research in this area.

The aim of the current research is to consider, from an ergonomic point of view, the criterion for the force required to open fire doors, and the required dimensions of fire

door frames, through conducting experimental studies on passing through fire doors. The current study implemented two types of experimental design, observing subjects passing through fire doors, and measuring the force required to open them. The experiments on passing through fire doors clarified the ability of subjects in manual wheelchairs to pass through the fire door under a variety of different experimental conditions. The experiments on measuring the force necessary to open fire doors clarified the physical abilities required to open such doors. In addition, by comparing the two sets of data, the relationship between the abilities of the subjects and the properties of the fire door were also clarified.

## 2. PREVIOUS RESEARCH AND RELATED LEGISLATION

In Japan, the issue of evacuating vulnerable persons including elderly and disabled people in emergency situations such as the outbreak of fire has not been subjected to sufficient debate. Even the Heartful Building Law revised in 2003 does not address the subject of the safety of disabled and elderly people when being evacuated. However, as the proportion of elderly people in Japan increases rapidly, it is desirable that all people are able to maintain their independence and participate actively in society. As such, the issue of dealing with the evacuation of vulnerable persons in emergency situations can no longer be put off. Further, awareness of responsibility for ensuring the safety of vulnerable persons is called for, such as the recognition of a hospital's responsibility for defects in safety procedures leading to incidents where partially paralyzed patients have fallen or suffered broken bones because they could not avoid closing fire doors. Particularly in public buildings, welfare facilities, and other buildings which are used by a large and undetermined number of persons, plans should be made which consider the safety of all building users.

According to Japan's Building Standards Law Enforcement Order Article 112, Paragraph 14, "fire prevention equipment must secure the safety of people around it when it is closed or when it is operated." However, there is no standard about opening force of fire door. So there is room for further research on the ability to pass through evacuation exits.

In Japan, much research on the safe evacuation of vulnerable persons focuses on measuring the maximum number of occupants under the evacuation plan and the physical capabilities of the occupants. Research on the opening and closing of doors includes numerous studies on the force required to open doors, the pushing force people exerted opening doors, and the angle subtended by the door when passage is possible. Research on hinged doors includes investigations of the relationship between the pushing force exerted by adult and juvenile men and women and the height of the handle, studies to determine the angle subtended by the open door, and studies in which non-disabled people using wheelchairs were subjected to sensory tests to investigate the relationships between subjects in sitting and standing positions, door configuration, the force required

to open the door, and ease of passage. Further, there is also a study on opening fire doors in high-rise apartments where a pressure differential either side of the door, assuming the activation of a smoke-control system, makes the door more difficult to open. Research which considers the perspective of vulnerable people includes an investigation into the state of regulations related to the force required by wheelchair users to open doors and the actual experimental measurement of that force for swing doors and sliding doors, and a study involving persons with restricted mobility which experimentally measured the force with which doors were closed by door closers, the percentage of subjects failed to pass through the door, and time taken to pass through the door. These studies have gathered important information useful for determining the force required to open doors. However, these studies do not provide detailed investigations of the width of fire doors and the actions of evacuees passing through fire doors.

The current study considers persons who are vulnerable in emergency situations to be those "whose physical capabilities are limited such that it impairs their ability to evacuate in emergency situations." In particular we focus on wheelchairs users, whose limited mobility restricts their ability to evacuate, placing them at higher risk than non-disabled people.

## 3. EXPERIMENT ON PASSING THROUGH A FIRE DOOR

### *3.1 Experimental research*

An experiment involving experimental subjects was carried out, simulating the passage of wheelchair users through hinged fire doors. *Figure 1* and *Figure 2* show summary diagrams of the experimental apparatus. The experimental apparatus simulates the type of fire door typically used in buildings, and is made of steel with an attached latch. In addition, because in emergency situations one pushes fire doors to open them, passing through the door was one way. The floor was covered with a PVC sheet.

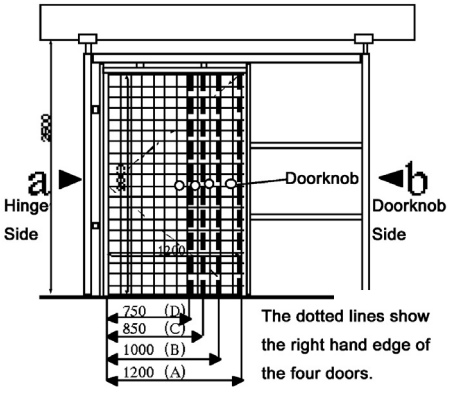


*Figure 1 Experimental apparatus - front view*

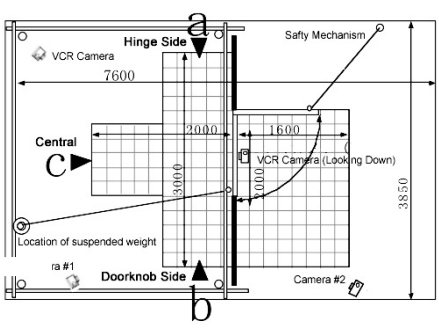


*Figure 2 Experimental apparatus - plan view*

The subjects passed through the door under a combination of the following experimental condition: Force required to open door: (20N, 30N, 40N, 50N, 70N, 80N, 100N, 120N); door frame width (1200mm, 1000mm, 850mm, 750mm); position of subject in relation to the door at the start of the experiment (hinge side (a), door knob side (b), central (c)); method of mobility; (walking, JIS large wheelchair, small non-JIS wheelchair). *Table 1* shows summary specifications of the two wheelchairs used in the experiment. To measure the effect of the type of wheelchair on the ability to pass through the fire door, two types of wheelchair were used: a JIS large wheelchair, which is normally used out of doors, and a smaller non-JIS wheelchair. Each configuration of passing through the door was combined with each level of force required to open the door, giving a total of 36 combinations. When a subject failed to pass through the door, the experiment was over and the configuration was changed. A total 871 trials were conducted. After each trial, subjects also filed in a response sheet stating whether they felt they were able to pass through the door safely. *Figure 3* shows the experiment in progress.

*Table 1 Wheelchairs used in the experiment*

| | Manufacturer Nissin<br>JIS Large | Manufacturer Wheely<br>Non-JIS Small |
|---|---|---|
| Model | Manual | Sport-type Manual |
| | NA-110A | SLA-20A |
| total length | 1040mm | 860mm |
| total width | 630mm | 550mm |
| total height | 900mm | 850mm |
| weight<br>seat area<br><br>seat height | 13.9 kg<br>400mm<br>Front of seat 460mm /<br>Rear of seat 440mm | 10.2 kg<br>320-380mm<br>Front of seat 430mm /<br>Rear of seat 370mm |
| distance from the rear of the seat to the front of the footrest | 760mm | 570mm |
| wheel size | 24 inches | 24 1/8 inches |
| caster size | 7 inches | 5 inches |


*Figure 3 Experiment in progress*

In the current study, subjects were selected in order to clarify the relationship between the physical capabilities of the subjects and the ability to pass through the fire door. Subjects, who represented wheelchair users, were non-disabled (five men, five women, (average age: 22, standard deviation 0.94)). In the interests of safety, senior citizens and disabled people were excluded from the subject group.

## *3.2 Force required to open the fire door, and the ability to pass through the fire door*

*Figure 4* and *5* show the number of men and women who failed to pass through the door under each of the experimental conditions. A comparison of male and female performance shows that while all subjects were able to pass through the door with a required opening force of up to 100 N when walking, a high percentage of women failed to pass through the door when using the wheelchair. All female subjects passed through the door with a required opening force of 20N and 30N, but as the required opening force increased passage became more difficult. At 70N 60% of female subjects failed to pass through the door, with all female subjects failing at 100N. Looking at the results by start position, subjects found it comparatively easy to pass through the door when starting on the hinge side or central position, but found it more difficult to pass through when starting on the door knob side. This is because the wheel chair and the door frame collide when the door is pushed, obstructing progress through the door. Additionally, when subjects used the smaller non JIS wheelchair, the success rate was higher. This is thought to be because the smaller chair made it easier to approach the door, and because the ease of operation of the smaller chair limited collisions with the door frame.

*Table 2 Configurations for passing through the fire door*

| Index | Mobility | Experimental Design | |
|---|---|---|---|
| A1 | *Walking* | Central position c) | Open with one hand |
| B1 | *JIS Wheelchair* | Hinge side position a) | Open with one hand |
| B2 | *JIS Wheelchair* | Doorknob side position b) | Open with one hand |
| B3 | *JIS Wheelchair* | Central position c) | Open with one hand |
| B4 | *JIS Wheelchair* | Central position c) | Use both hands and grab door frame |
| B5 | *Smaller non JIS Wheelchair* | Position different for each subject | Open with one hand |

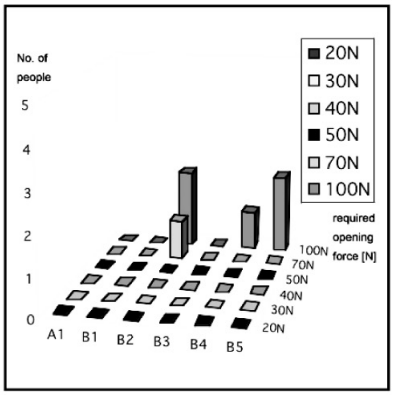


*Figure 4 No. of men failing to pass through fire door*

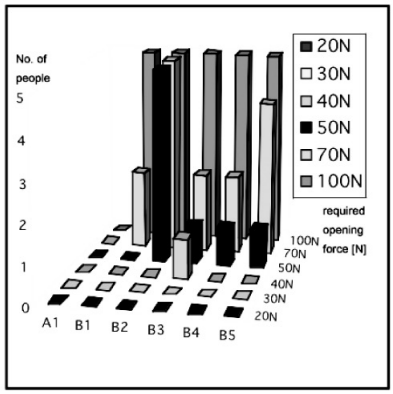


*Figure 5 No. of women failing to pass through fire door*

## 3.3 Width of fire door and possibility of safe passage

*Figure 6* shows the number of subjects successfully passing through the door according to the force required to open the door and each door width, wheelchair type and start position. The results show the number of women failing to pass through the door, the number of men failing to pass through the door, and the number of successful passes. Further, if the difference in failure rates between adjacent graphs are significant, significance levels are listed. When using the large wheelchair, starting from the hinge side, success rates are almost identical whether the door width is 1200mm or 1000mm, with all subjects successful up to a required opening force of 60N. With door widths of 850mm or less, failure rates start to increase. It can be seen that 1000m provides sufficient width to pass through the door. When using a large wheelchair, starting from the door knob side, there is a significant difference ($p<0.01$) between failure rates at 850mm and 750mm. The results suggest that 750mm is not sufficient width to maneuver a wheelchair through the door. However, the failure rate was lower as for the smaller wheelchair, as it is easier to maneuver and not as wide.

Regarding start position, the failure rate is significantly higher when starting on the door-knob side than when starting on the hinge side ($p<0.05$). This is thought to be because when starting on the door-knob side, it is necessary to open the door while changing the direction of the wheelchair, meaning it is difficult for the subjects to gain leverage on the handle, in addition to the complex operation of the wheelchair. In other words, when starting on the hinge side, passage becomes impossible because the maximum force that can be exerted by the subject is less than the force required to open the door. When starting from the door knob side, the difficulty of the wheelchair maneuver enters the equation, in addition to the relationship between these two forces.

There is a large difference in the required opening force at which men and women can pass through the door successfully. When approaching from the door-knob side, female subjects could also pass through the door when the force required to open it was 50N,

but when approaching from the hinge side 40 N was the limit. All subjects, under all conditions were able to pass through the door when the forced required to open it was 30N. When starting from the door-knob side, some examples were seen in which the wheelchair's hand rims caught on the frame of the fire door, preventing passage through the door. When subjects used the smaller wheelchair they were able to benefit from additional mobility. However, when the force required to open the fire door was great, some examples were seen in which the wheelchairs tires skidded, and subjects were unable to pass through the door.

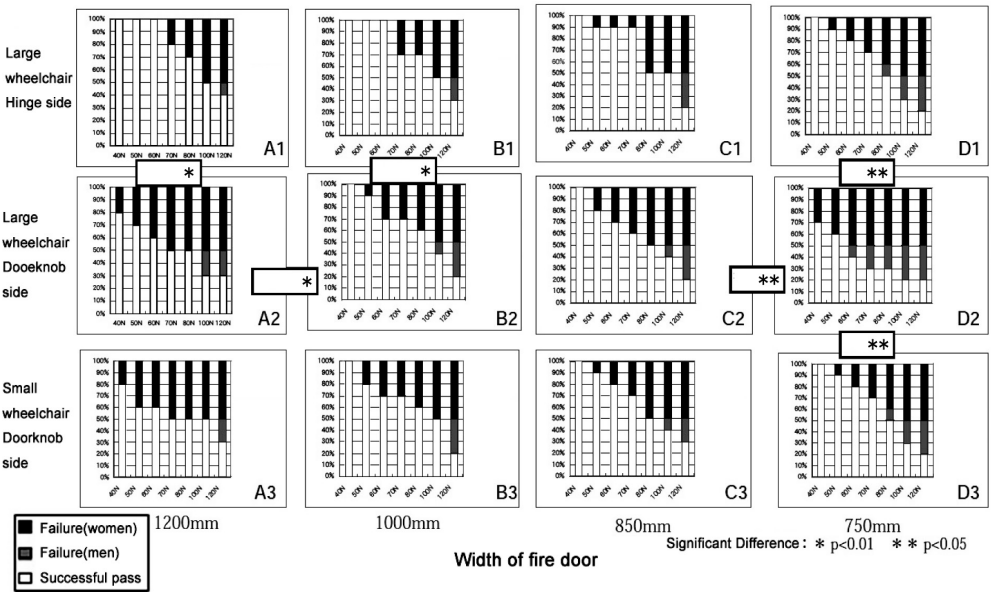


*Figure 6 Force required to open fire door* and *successful or failed pass through fire door*

# 4. EXPERIMENT TO MEASURE PUSHING FORCE EXERTED WHEN OPENING A FIRE DOOR

## *4.1 Experimental method*

An experiment was conducted to simulate the pushing action made when passing through a hinge-type fire door, and the pushing force exerted on the door by experimental subjects was measured (*Figure 7*). Using the measuring apparatus shown in *Figure 8*, the pushing force exerted by subjects on a vertical surface was measured under different experimental conditions. The flooring and subjects' shoes were identical to those used in the fire door passage experiment above. Experimental conditions, which were based on the fire door passage experiment, were position; (hinge side (right side), door knob side (left side) and central) and the method of mobility (walking, large JIS wheelchair, smaller non-JIS wheelchair).

At a given sign, subjects pushed on a measuring device for four seconds. Measurements were taken and recorded twice for each experimental condition. The height of the measuring device was adjusted according to each subject and category in order to allow the exertion of the maximum possible force. The experimental conditions correspond to those in experiment on passing through a fire door. Under Condition A subjects stand (corresponding to walking) while under condition B subjects use a wheelchair.

The measuring device was manufactured by Kistler Inc. (Product ID number 9281c). The device was attached in a vertical position, and connected to a computer. (Data was recorded using an input and analysis program, Wad Ver. 1.71. by DKH Inc.) To adjust the device to a height at which subjects could push the device easily, a height adjuster was fitted. The device can measure force exerted by the subjects over time on three axes, the in-plane vertical (Fx), in-plane horizontal (Fy) and out-of-plane horizontal (Fz) (*Figure 8*).

*Figure 7 Experiment to measure pushing force in progress*

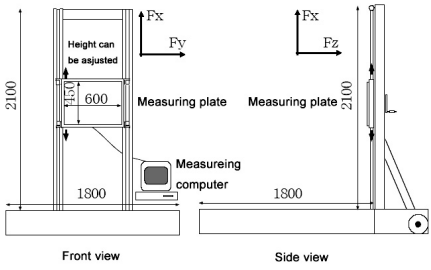


*Figure 8 Summary of apparatus to measure pushing force*

Subjects were young people (five men, five women, (average age 22, standard deviation 0.94) and senior citizens who had no difficulty going about their daily routine (three men, three women, (average age 73, standard deviation 2.76). To facilitate comparison with the experiment on passing through a fire door, the same young people participated in the pushing force experiment.

The "pushing force" exerted by the subjects was analyzed as follows. "Pushing force" was defined as the force exerted by subjects on the fire door to push it open and pass through. In order to pass through a fire door, it is necessary to press on the fire door continuously. We discounted the initial application of pressure and the final releasing of pressure, and took the average force in the out-of-plane horizontal direction (Fz) to be the continuous pushing force.

## *4.2 Results and observations of experiment to measure continuous pushing force on fire doors*

The arithmetic mean continuous pushing force calculated from all experimental subjects under each experimental condition is shown in *Figure 9* and *10*. The extremities

of each line show the highest and lowest individual scores. The mid-point is the average reading, and the vertical line shows the range of observed data.

Pushing force is largest among young men, then young women, followed by older men and older women. Older women could exert a maximum force of around 40N, even when standing and pushing with both hands. When standing, the pushing force exerted by older men is 60% that of younger men.

An examination of each experimental condition shows that, when standing, the pushing force exerted by one hand is 81% that of the force exerted by both hands. In the case of younger subjects, the pushing force exerted when using a wheelchair is 70% of the force exerted when walking. The weak pushing force of elderly female subjects appears to be influenced by a lack of leg strength preventing sufficient traction with the ground (*Figure 10*).

When using a wheelchair, no difference is observed in the pushing force exerted when facing left or facing right. However, the force exerted when facing in the direction of the door falls to 68% of the force exerted when facing left or right. When facing in the direction of the door, subjects must exert pressure on the hand rim to prevent the wheelchair from moving, which results in a particularly unstable posture.

An examination of the differences between the types of wheel chair used show that the pushing force exerted by subjects in the smaller wheelchair is equivalent to 94% that of subjects in the larger JIS wheelchair, because increased instability tends to cause a slight reduction in the force that can be applied.

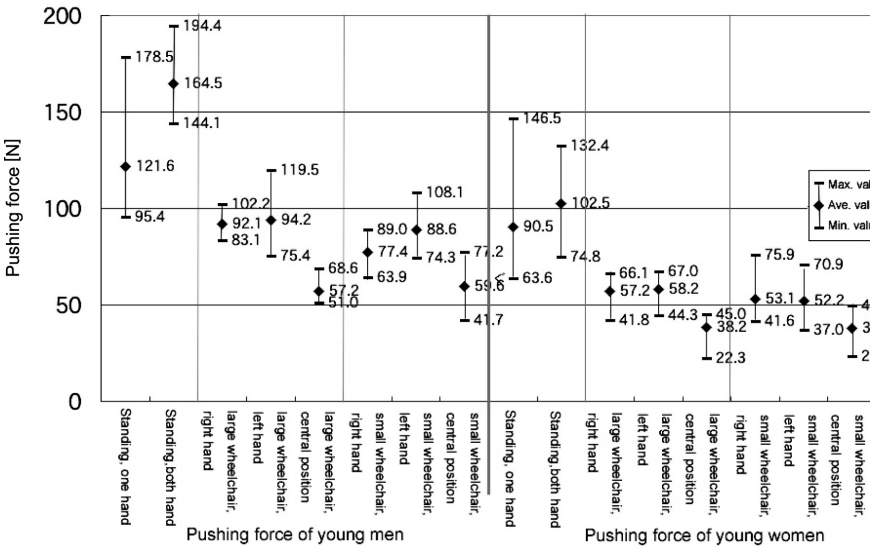


*Figure 9 Results of pushing force measurements in younger subjects*

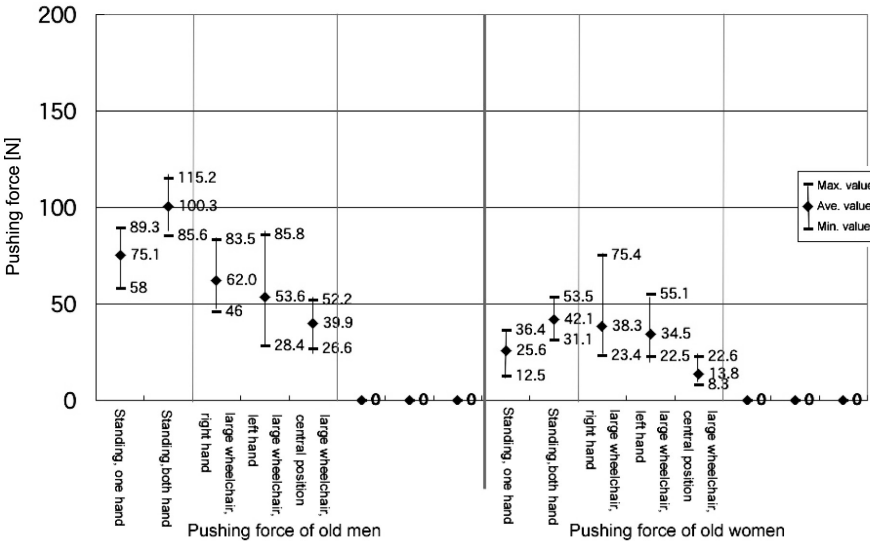


*Figure 10 Results of pushing force measurement in older subjects*

## 5. RELATIONSHIPS BETWEEN PUSHING FORCE AND REQUIRED OPENING FORCE FOR PASSABLE FIRE DOORS

The door with the maximum required opening force through which individual subjects could pass in experiment on passing through a fire door was compared with their maximum pushing force in the experiment to measure pushing force (*Figure 11*). When standing or using the wheelchair on the left side, subjects were able to pass through fire doors with a required opening force equal to their pushing force. On the other hand, when using the wheelchair on the right side, subjects were sometimes unable to pass through doors with a required opening force lower than their pushing force. This is because, when approaching the door from the right side, subjects must rotate the wheelchair as they pass through the door. As such the difficulty of the maneuver affects results, in addition to the subjects pushing force. When using the wheelchair facing the door, subjects were able to pass through fire doors with a required opening force in excess of their pushing force. This is because subjects were unable to exert sufficient pressure on the measuring device, and the measurements of pushing force underestimated their true pushing force. The results show that depending on the direction from which the door is approached, there are some cases where wheelchair users cannot pass through a fire door even if the required opening force is less than their pushing force.

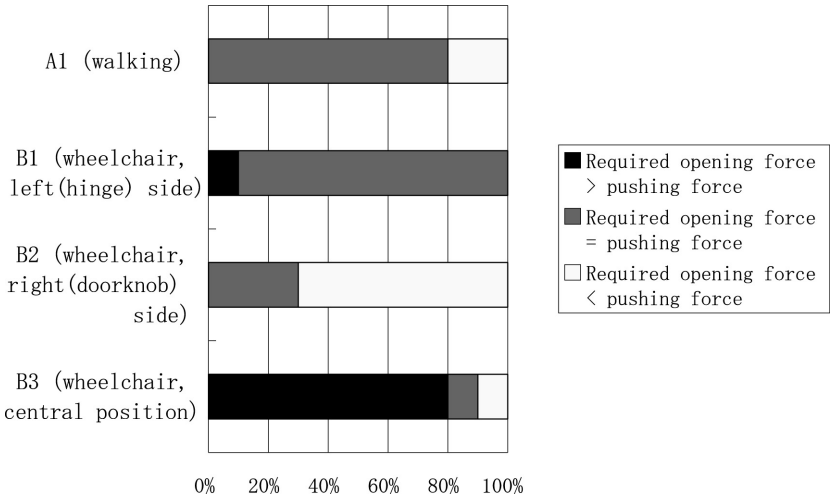


*Figure 11 A comparison of maximum pushing force* and *the required opening force of fire doors through which subjects could pass*

## 6. CONCLUSION

The results of the current study show that it is desirable for fire doors to have a required opening force of no more than 40N and a width of more than 850mm. However, the experimental subjects were not disabled, the results may differ from disabled occupants. And because the physical capabilities of wheelchair users vary widely, further research and experiments are gain a fuller understanding of the situation.

When using a wheelchair, the direction from which the door is approached has a significant impact on whether or not the subject can pass through the door. In particular, when approaching from the door knob side, many instances were observed in which subjects failed to pass through the door even though they were able to push it open, because the wheelchair collided with the door frame. From these observations, it is postulated that in cases where corridors are narrow and there is not sufficient room to maneuver a wheelchair, a wheelchair user will often be unable to evacuate safely to the stairwell if they approach the fire door from the door knob side. Differences were also observed depending on the type of wheelchair used. Compared to a larger wheelchair, a smaller wheelchair was more unstable. Despite this, the increased maneuverability of the smaller wheelchair led to a reduction in the number of failures to pass through the door. One method used by wheelchair users to open a door is to maneuver the wheelchair parallel to the door, and open the door while facing sideways. This method allows doors to be opened with relatively little force. However, the preferable orientation depends on the position of the hinge and which is the wheelchair users stronger arm.

Therefore it is essential that there is sufficient space in front of the fire door to bring a wheelchair parallel to the door, and also to rotate the wheelchair 180 degrees when

necessary. Such considerations should be considered at the building design stage. And it is desirable for fire doors in the building to have a required opening force of no more than 40N and a width of more than 850mm.

Going forward, further experimentation involving regular wheelchair users, and the analysis of a wider range of data is called for.

## REFERENCES

1. K.E.Boyce T.J.Shields et.al 1999 : Toward the characterization of Building Occupancies for Fire Safety Engineering: Capabilities of disabled People to Negotiate Doors. Fire Technology, Vol.35, No.1, p.68-78
2. K.E.Boyce T.J.Shields et.al 1999 : Toward the characterization of Building Occupancies for Fire Safety Engineering: Capabilities of disabled People Moving Horizontally and on an Incline. Fire Technology, Vol.35, No.1, p.51-67
3. Daniel Joyeux, 2002 : Experimental investigation of fire door behaviour during a natural fire, Fire Safety Journal 37, 605–614
4. National Institute of Standards and Technology, 1995, Emergency Procedures for Employees with Disabilities in Office Occupancies, United States Fire Administration, Emmitsburg, MD, p.26
5. Nelson, H. E., 1993, "Fire Modelling Assessment of Areas of Refuge Intended to Provide Safety for Persons with Mobility Limitations", Conference Proceedings of Interflam '93,C. A. Franks (Ed.), Oxford, England, March 30-April 1 1993, pp. 161-168.
6. Pauls, J. and Juillet, E., 1993, "Life Safety of People with Disabilities: How Far Have We Progressed? ", Proceedings - Symposium: Engineering Fire Safety in the Process of Design, University of Ulster at Jordanstown, Newtownabbey, , Part 2, pp. 17-40.
7. T.Sano, K.Tatebe, I.Hagiwara, Y.Mimura, M.Honma 2002 : Characteristics of People Vulnerable to Disasters Passing through the Fire-resistive Assembles for Protection of Opening. Journal of Archit. Plann. Environ. Eng., AIJ, No.559, pp.1-7 (In Japanese)
8. K.Tatebe, T.Sano, I.Hagiwara, M.Honma, Y.Mimura , S.Uchiyama 2004: A motion characteristics passing through the opening of fire equipment, Journal of Archit.Plann. , NO.576 , pp.53 (In Japanese)