Evaluation of Evacuation Time for Each Evacuation Equipment in Neighborhood Facilities: Focused on Descending Lifeline and Elevating Equipment for Evacuation

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Abstract: At present, the standard for installing evacuation equipment that enables occupants to evacuate on their own is determined by the use of a building and its floor area. However, according to the "Installation Maintenance and Safety Control of Fire-Fighting Systems Act" and "Fire Safety Standards for evacuation equipment", the installation standard for evacuation equipment mentions only the minimum number of equipment to be installed based on the floor area. Thus, this installation standard fails to reflect the corresponding number of occupants in a building and the effectiveness of the evacuation equipment. Thus, there is a high probability that most of the evacuation equipment installed based on the "one-size-fits-all" legal regulation will not guarantee the safety of occupants in case of a fire. To address this, the performance evaluation of the effectiveness of evacuation and the distribution ratio of equipment per occupant needs to be prioritized. Therefore, we conduct mock experiments on the descending lifeline and elevating evacuation equipment to analyze their efficiencies. Moreover, we propose a model for calculating the evacuation time for the descending lifeline and elevating evacuation equipment based on the experimental results. Furthermore, we conduct effectiveness evaluation by using the evacuation equipment. The results show that most people cannot be evacuated using the evacuation equipment. That is, evacuation equipment was determined to be insufficient for ensuring safety as per the current standard. Therefore, the installation of evacuation equipment according to its efficiency and capacity is considered necessary.

Keywords: Evacuation equipment; Descending lifeline; Elevation equipment

1. Introduction

In South Korea, the number of densely populated areas has increased owing to urbanization accompanied by rapid industrialization and economic development. However, the number of fire victims is increasing because safety management awareness and technological development for fire safety have been unable to meet the needs of the times. In addition, actual fire cases continuously show firefighting and rescue problems, such as firefighters entering a building and unable to leave owing to insufficient air or water that does not reach upper floors. To ensure the safety of occupants in case of a fire, enabling them to evacuate on their own is crucial. Accordingly, occupants need to be aware of evacuation routes, learn how to use evacuation equipment, and utilize them actively to evacuate on their own.

The types of evacuation equipment for the safe evacuation of occupants and the relevant installation standards are presented in National Fire Safety Code (NFSC) 301\textsuperscript{[1]}. The evacuation equipment presented in NFSC 301 includes evacuation ladders, descending lifelines, simple descending lifelines, rescue sacks, air safety mats, multiperson evacuation apparatus, and descending ladders for downward evacuation. The installation standards for such evacuation equipment are determined by the building use and total floor area. However, such standards do not consider the
efficiency and installation location of each evacuation device, and the number of evacuation devices to be installed is specified only according to the total floor area of the facility. The evacuation equipment installed based on the indiscriminate legal regulation without considering evacuation efficiency cannot guarantee the safety of occupants in the event of a fire. To address this problem, the evacuation efficiency of each evacuation device must be analyzed. Based on this, evacuation equipment must be installed.

Therefore, in this study, evacuation experiments were performed using elevating evacuation equipment and a descending lifeline to analyze the evacuation efficiency, which is required to derive installation standards for evacuation equipment. Based on the experiment results, models for calculating the evacuation time of the elevating evacuation equipment and descending lifeline were developed. The evacuation time of each evacuation device was compared with that of evacuation devices in previous studies to analyze their evacuation efficiency.

2. Problems with Installation Standards for Evacuation Equipment

In this study, neighborhood facilities were intensively analyzed based on various building types (uses). To analyze the fire risk of such facilities, the number of fires and the number of human casualties for each building use over the last three years were investigated and are summarized in Table 1. As evident from the table, neighborhood facilities show the largest number of fires (4,238). Apartments show the largest number of human casualties (321), followed by neighborhood facilities (260). The number of fires is high for neighborhood facilities owing to the concentration of large floating populations caused by the spatial characteristic that several facilities are contained in one building. The number of fires and the number of human casualties are considered to be large in neighborhood facilities because illegal repair is frequently performed to satisfy customer requirements and achieve economic profits[2]. Accident cases were investigated to analyze the fire risk of neighborhood facilities. Representative cases include the fires at Yeji Academy in Gwangju (2001), a postpartum care center in Jinju (2002), Nau goshiwon in Seoul (2006), and a goshiwon in Yongin (2008). The common characteristics of these fire accidents were high population density and narrow evacuation routes.

<table>
<thead>
<tr>
<th>Category</th>
<th>Number of Fires</th>
<th>Number of Human Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neighborhood Facilities</td>
<td>4,238</td>
<td>260</td>
</tr>
<tr>
<td>Apartments</td>
<td>2,599</td>
<td>321</td>
</tr>
<tr>
<td>Factories</td>
<td>2,240</td>
<td>136</td>
</tr>
<tr>
<td>Complex Buildings</td>
<td>709</td>
<td>40</td>
</tr>
<tr>
<td>Animal-/plant-related Facilities</td>
<td>314</td>
<td>10</td>
</tr>
<tr>
<td>Accommodation Facilities</td>
<td>295</td>
<td>88</td>
</tr>
<tr>
<td>Cultural Assembly/Sports Facilities</td>
<td>134</td>
<td>4</td>
</tr>
<tr>
<td>Medical Facilities</td>
<td>74</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 1: Number of Fires and Number of Human Casualties Based on Building Type

In several neighborhood facilities, several facilities are located in one building, resulting in large floating populations and high occupant density. This may cause many human casualties in the event of a fire. In accordance with Article 34[3] of the Enforcement Decree of the Building Act, two or more direct stairways must be installed if the area used as a neighborhood facility is 200 m² or larger. However, the analysis of the aforementioned accident cases revealed that many of them occurred in a space smaller than 200 m². In this instance, damage increased because direct stairways were blocked by fire and smoke. This indicates that there is no evacuation route that occupants can choose if stairs are closed owing to flames and smoke in a fire situation. In this case, occupants are forced to wait for rescue or evacuate by relying on evacuation equipment. However, in the case of neighborhood facilities, one or more evacuation devices must be installed for every 500 or 800 m² in accordance with the NFSC. Therefore,
efficient evacuation in neighborhood facilities with large floating populations and high occupant density using one evacuation device is challenging. In addition, as no standard is established for the selection of evacuation equipment, descending lifelines, which require a small space and are inexpensive, are mainly installed according to previous studies. Ensuring the safety of occupants by installing the evacuation equipment arbitrarily selected by the designer or building owner rather than installing evacuation equipment based on its efficiency is considered to be impossible. To address this problem, the efficiency of each evacuation device should be determined. Accordingly, the evacuation equipment needs to be installed considering complex factors, such as the use of the building, number of people expected to use the equipment, and installation location.

First, previous studies on the efficiency of evacuation equipment were analyzed. Kim[4] performed a simulated evacuation experiment at a drill tower and analyzed the time required when a spiral suit and an articulated ladder truck were used. Park[5] analyzed the most commonly used evacuation equipment in Korea by conducting a survey and investigated the reason for using the equipment by performing a post-interview. According to the results of the survey, the proportion of using descending lifelines was approximately 77%; moreover, descending lifelines were used because their installation is simple and they can be installed in a small area. The necessity of evaluation equipment was emphasized in several previous studies[6-10], but the performance of evacuation equipment was quantitatively analyzed through mock-up experiments in only a few studies. Thus, in this study, mock-up experiments were performed to quantitatively analyze the performance of a descending lifeline, which is most commonly used in Korea, and elevating evacuation equipment, which is evaluated to be highly suitable for high-rise buildings.

3. Experimental Method

3.1 Experimental scenario design

Based on the aforementioned fire accident cases and the analysis of related regulations, an experimental scenario and a target site were selected. When the aforementioned fire accident cases were analyzed, several neighborhood facilities with extensive fire damage were found to have one direct stairway toward the ground floor. In this instance, the damage was observed to be extensive when evacuation to the stairs was impossible owing to such reasons as the occurrence of smoke in the staircase and the fire moving to objects stacked on the stairs. In accordance with the Enforcement Decree of the Building Act, two or more direct stairways must be installed in neighborhood facilities with an area of 200 m², and evacuation equipment must be installed for every 500 m² in medical and accommodation facilities and every 800 m² in recreational, sports, and sales facilities. Therefore, in this study, a neighborhood facility with an area smaller than 200 m² and one direct stairway, which has a high fire risk, was selected as the target site, and mock-up experiments were performed for each evacuation device. In addition, the experiments were performed on the 3rd floor to analyze the movement time with each evacuation device for each floor. In the experiments, a descending lifeline, which is used in most neighborhood facilities, and elevating evacuation equipment were used. The mock-up evacuation experiment using a descending lifeline was performed at the descending lifeline experience center located in Busan under the cooperation of the Saha Fire Station in Busan.

The mock-up experiment using elevating evacuation equipment was performed in the Milmaru Welfare Village located in Sejong City. The village is a welfare building for the elderly, which has facilities for the elderly on the 1st and 2nd floors and houses from the 3rd to 14th floors. The location of the experimental place was set from the 3rd floor to the ground floor to match the height with the descending lifeline experiment.

Figure 1 shows the site of full-scale experiment using the descending lifeline and the elevating evacuation equipment.
3.2 Overview of the descending lifeline and elevating evacuation equipment

The descending lifeline and elevating evacuation equipment used in this study are defined as follows. A descending lifeline is a device that automatically descends with the user's weight by installing a support on a building wall and hanging a rope. It is classified into two types: one that can be continuously used by users and another that does not rise again after descending once. A descending lifeline consists of a speed governor, a connection part of the speed governor, rope, connecting metal ball, and belt. It is specified as a structure that withstands a maximum load of 1,500 N (150 kg). Its descending speed must be in the range of 16-150 cm/s. Descending lifelines are the most commonly used evacuation equipment for up to the 10th floor, and cannot be used on the 11th or higher floors under the current legal system. It is difficult to use a descending lifeline if the user has no prior knowledge on it or no experience of using it, and it requires considerable evacuation time. As descending lifelines operate through the outside of the balcony, using them on floors higher than the floor on which the fire accident has occurred is difficult. People with disabilities, children, elderly people, and women have difficulty using them. Recently, the capacity of descending lifelines has been increased to 150 kg considering user weight exceeding 100 kg or use by two people. In addition, descending lifelines are simple and easy to use and are mainly installed in low-rise accommodation facilities or group accommodations, such as dormitories; however, prior education or training is required as they shake while descending.

Elevating evacuation equipment consists of a boarding plate, handle bar, and a body to adjust the descending speed. Its structure is similar to that of a simple descending lifeline. While the evacuee wears a belt to descend for a descending lifeline, elevating evacuation equipment slowly descends to lower floors under the weight of the evacuee when the evacuee steps on the boarding plate. Elevating evacuation equipment can evacuate several people within a short duration, as the spring returns to its original shape and the boarding plate rises again once it reaches the bottom floor. As it is installed in indoor spaces and descends by one floor at a time without the influence of external wind, the evacuee on the boarding plate can slowly descend in a stable manner without fear. Elevating evacuation equipment can operate even in the event of a power outage owing to a fire accident because it requires no separate power source and descends based on the evacuee’s weight (weight range: 20 to 120 kg) and gravity. It descends by one floor at a time until it reaches the ground floor. It can be used even on the 11th or higher floors regardless of the number of floors in a building. It is easy to maintain owing to its simple structure, and can be used easily by anyone, as it descends when the descending button is pressed after the evacuee steps on the boarding plate without complicated manipulation.
3.3 Experiment participants

Forty subjects (39 male and one female) participated in the mock-up experiment on the descending lifeline. Among them, 36 participants were in their teens and four were in their twenties. The average height of the participants was 171 cm, and the average weight was 61 kg. They had no motor disabilities because they had to wear the descending lifeline on their own. There was a possibility of a safety accident because people usually have no experience of wearing a descending lifeline. Therefore, the experiment was performed under the control of safety personnel. However, intervention by the personnel was minimized during the course of wearing the descending lifeline and descending using it.

Twenty subjects (four male and 16 female) participated in the mock-up experiment on the elevating evacuation equipment. Among them, 13 participants were in their sixties, one was in their forties, one was in their thirties, and five were in their twenties. They had no motor disabilities because they also had to use the elevating evacuation equipment on their own. The entire process for the mock-up experiments on the descending lifeline and elevating evacuation equipment was recorded using a camcorder.

4. Experimental Results

4.1 Analysis of the evacuation time of the descending lifeline

For a precise analysis of the evacuation time of the descending lifeline, steps were classified according to the sequence of use of the descending lifeline in this study as shown in Table 2. The entire process of using the descending lifeline by the participants consists of preparation, wear, descent, and belt-removal steps according to the sequence of use. The sequence is composed of the following four steps: a preparation step in which the support is taken out and installation is complete, a wear step in which the descending lifeline is put on, a descent step in which evacuation is performed along the wall, and a belt-removal step in which the belt is removed and evacuation is complete.

<table>
<thead>
<tr>
<th>Step</th>
<th>Use Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparation</td>
<td>1) The support is taken out of the window.</td>
</tr>
<tr>
<td></td>
<td>2) The descending lifeline hook is hung on the support ring.</td>
</tr>
<tr>
<td></td>
<td>3) The reel is thrown out of the window.</td>
</tr>
<tr>
<td>Wear</td>
<td>4) The descending lifeline belt is fastened around the chest.</td>
</tr>
<tr>
<td></td>
<td>5) Sit safely on the window sill.</td>
</tr>
<tr>
<td>Descent</td>
<td>6) Descend safely along the wall.</td>
</tr>
<tr>
<td>Belt Removal</td>
<td>7) The belt is removed upon the completion of evacuation.</td>
</tr>
</tbody>
</table>

The evacuation time of the descending lifeline was analyzed for the 40 participants. The preparation step, which is performed only once by the participant who evacuates first, required approximately 60 s on average. The average time required for each step is shown in Table 3. Figure 2 shows the distribution of the required time. The average wearing time is 25.6 s, and the standard deviation is 9.8. The average descending time is 8.1 s, and the standard deviation is 1.1. The average belt-removal time is 8.6 s, and the standard deviation is 3.1. The wear step exhibits a large standard deviation value compared with the other steps because significant differences are present in the time required by the participants to sit on the window sill owing to personal fear. Finally, the total time required to evacuate from the 3rd floor using the descending lifeline shows an average of 42.2 s and a standard deviation of 11.2.
### Table 3. Average Time Required for Each Step in Using the Descending Lifeline

<table>
<thead>
<tr>
<th>Category</th>
<th>Wear (s)</th>
<th>Descent (s)</th>
<th>Belt Removal (s)</th>
<th>Evacuation Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>25.6</td>
<td>8.1</td>
<td>8.6</td>
<td>42.2</td>
</tr>
<tr>
<td>Number of Samples</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>9.8</td>
<td>1.1</td>
<td>3.1</td>
<td>11.2</td>
</tr>
</tbody>
</table>

#### Figure 2. Analysis of the time required for each step in using the descending lifeline.

### 4.2 Analysis of the evacuation time of the elevating evacuation equipment

Prior to the mock-up experiment on the elevating evacuation equipment, the participants were educated on the entire process of how to use the evacuation equipment to prevent safety accidents. For a precise analysis of the evacuation time, steps were classified according to the sequence of use of the elevating evacuation equipment as shown in Table 4. The process of using the equipment for evacuation by the participants consists of preparation, descent, and get-off steps according to the sequence of use.

### Table 4. Classification of the Steps According to the Sequence of Using the Elevating Evacuation Equipment

<table>
<thead>
<tr>
<th>Step</th>
<th>Use Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparation</td>
<td>1) Step on the elevating evacuation equipment.</td>
</tr>
<tr>
<td></td>
<td>2) Press the pedal on the floor.</td>
</tr>
<tr>
<td>Descent 1</td>
<td>3) Descend safely.</td>
</tr>
<tr>
<td>Transfer</td>
<td>4) Get off and step on the next elevating evacuation equipment.</td>
</tr>
<tr>
<td></td>
<td>5) Press the pedal on the floor.</td>
</tr>
<tr>
<td>Descent 2</td>
<td>6) Descend safely.</td>
</tr>
<tr>
<td>Get-off</td>
<td>7) Get off the equipment.</td>
</tr>
</tbody>
</table>

As the elevating evacuation equipment descends by one floor, the next elevating evacuation equipment is used to move one more floor. Therefore, in the evacuation experiment of this study, where evacuation was performed for two floors from the 3rd floor to the ground floor, the sequence of using the elevating evacuation equipment involved five steps, including two descent steps and a transfer step. In the experiment, the participants move to the 2nd floor through the descent 1 step after the preparation step in which they step on the elevating evacuation equipment on the 3rd floor and press the pedal on the floor. They transfer to the next elevating evacuation equipment after getting off the first equipment in the transfer step, move to the ground floor through the descent 2 step, and finally complete evacuation through the get-off step. The average time required for each step is summarized in Table
5. Figure 3 shows the distribution of the evacuation time. The total evacuation time yields an average of 43.6 s and a standard deviation of 10.7. The preparation step requires 7.5 s on average, and the standard deviation is 5.8. Descent 1 from the 3rd floor to the 2nd floor requires 12.7 s on average, and the standard deviation is 1.7. The transfer step requires approximately 9.3 s on average, and the standard deviation is 3.5. Descent 2 from the 2nd floor to the 1st floor requires 7.8 s on average, and the standard deviation is 0.6. The final get-off step requires 6.3 s on average, and the standard deviation is 2.8.

Table 5. Average Time Required for Each Step in Using the Elevating Evacuation Equipment

<table>
<thead>
<tr>
<th>Category</th>
<th>Preparation</th>
<th>Descent 1</th>
<th>Transfer</th>
<th>Descent 2</th>
<th>Get-off</th>
<th>Evacuation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (s)</td>
<td>7.5</td>
<td>12.7</td>
<td>9.3</td>
<td>7.8</td>
<td>6.3</td>
<td>43.6</td>
</tr>
<tr>
<td>Number Samples</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>5.8</td>
<td>1.7</td>
<td>3.5</td>
<td>0.6</td>
<td>2.8</td>
<td>10.7</td>
</tr>
</tbody>
</table>

Figure 3. Analysis of the time required for each step of use of the elevating evacuation equipment.

The standard deviation was large in the preparation, transfer, and get-off steps, whereas it was small in the descent 1 and descent 2 steps. For the descent time, no significant difference was present, depending on the characteristics of the participants because the equipment was automatically operated according to their weight. However, in the case of the preparation, transfer, and get-off steps, significant differences were present, depending on the age of the participants. Therefore, the participants were divided into two groups: over and under the age of 60; the average time required for each step by each group was analyzed. The analysis results are summarized in Table 6, and the evacuation time is shown in Figure 4. For the group under the age of 60, no significant difference exists in the standard deviation for each step. However, in the case of the group over the age of 60, the standard deviations of the preparation, transfer, and get-off steps are large and those of the descent 1 and descent 2 steps are small. This indicates a significant difference in the time required depending on the physical characteristics of each individual in the group over the age of 60. In addition, the group over the age of 60 requires more time on average for all steps than the group under the age of 60. The difference in the average time required is larger in the preparation, transfer, and get-off steps. In the case of the descent steps where the equipment is moved automatically according to the participant’s weight, no significant time difference is observed.
Table 6. Average Time Required for Each Step in Using the Elevating Evacuation Equipment

<table>
<thead>
<tr>
<th>Category</th>
<th>Preparation</th>
<th>Descent 1</th>
<th>Transfer</th>
<th>Descent 2</th>
<th>Get-off</th>
<th>Evacuation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group Over the Age of 60</td>
<td>9.5</td>
<td>13.2</td>
<td>11.1</td>
<td>7.8</td>
<td>7.8</td>
<td>49.4</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>6.3</td>
<td>1.7</td>
<td>2.8</td>
<td>0.6</td>
<td>2.1</td>
<td>8.3</td>
</tr>
<tr>
<td>Group Under the Age of 60</td>
<td>3.7</td>
<td>11.6</td>
<td>6.0</td>
<td>7.7</td>
<td>3.6</td>
<td>32.6</td>
</tr>
<tr>
<td>Average (s)</td>
<td>0.8</td>
<td>1.3</td>
<td>1.9</td>
<td>0.8</td>
<td>1.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Figure 4. Comparison of the evacuation time using the elevating evacuation equipment based on participant age.

5. Discussion

5.1 Comparison of the evacuation time between the descending lifeline and elevating evacuation equipment

To compare the mock-up experiment results for the descending lifeline and elevating evacuation equipment, the corresponding four and five steps in using the evacuation equipment were reclassified into the following three steps: preparation, descent, and end steps. For the descending lifeline, the four steps (preparation, wear, descent, and belt-removal steps) were reclassified into the three aforementioned steps by integrating the preparation and wear steps into the preparation step and considering the belt-removal step as the end step. In the case of the elevating evacuation equipment, the five steps (preparation, descent 1, transfer, descent 2, and get-off steps) were reclassified into the three aforementioned steps by integrating the descent 1, transfer, and descent 2 steps into the descent step and considering the get-off step as the end step.

Table 7. Comparison of the Average Time Required between the Descending Lifeline and Elevating Evacuation Equipment

<table>
<thead>
<tr>
<th>Category</th>
<th>Preparation Step</th>
<th>Descent Step</th>
<th>End Step</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descending Lifeline</td>
<td>Wear 25.6</td>
<td>Descent 8.1</td>
<td>Belt Removal 8.6</td>
<td>42.2</td>
</tr>
<tr>
<td>Elevating Evacuation Equipment</td>
<td>Preparation 9.5</td>
<td>Descent 1 + Transfer + Descent 2 32.1</td>
<td>Get-off 7.8</td>
<td>49.4</td>
</tr>
<tr>
<td>(over the age of 60)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevating Evacuation Equipment</td>
<td>Preparation 3.7</td>
<td>Descent 1 + Transfer + Descent 2 25.3</td>
<td>Get-off 3.6</td>
<td>32.6</td>
</tr>
<tr>
<td>(under the age of 60)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7 shows the average time required for each step of the descending lifeline and elevating evacuation equipment. In the case of the elevating evacuation equipment, the participants were divided into a group over the age of 60 and a group under the age of 60, and the average time required for each step was analyzed. When the time required for each step was compared between the evacuation devices, it was observed that the descending lifeline required considerable time for wearing and preparation in the preparation step, whereas the elevating evacuation equipment required less time as it descended with the participants pressing the pedal on the footplate with no separate preparation. In the descent step, the time required by the descending lifeline was short because there was no need to transfer during descent. In the case of the elevating evacuation equipment, the evacuation time was relatively longer, as transferring to the next evacuation equipment was necessary. In the end step, the descending lifeline required a relatively long time for the belt removal, but the elevating evacuation equipment required less time. In addition, in the case of the elevating evacuation equipment, the evacuation time differed by approximately 17 s between the group over the age of 60 and the group under the age of 60, indicating a significant difference in evacuation time depending on the age. As the elevating evacuation equipment required considerable time for descent, which included the descent and transfer steps, compared with the descending lifeline, its evacuation time was expected to be further increased as the number of floors increased.

5.2 Derivation of evacuation time calculation models

Based on the analyzed evacuation time for each step, models for calculating the evacuation time of the descending lifeline and elevating evacuation equipment were developed. The models were prepared based on the average time required for each step as follows. For evacuation using the descending lifeline, evacuation was performed through the initial installation time, preparation step, descent step, and end step. Consequently, the time required for N people to evacuate using the descending lifeline is expressed as Eq. (1).

\[
\text{Evacuation time (seconds) = initial installation time + \left(\text{preparation step + descent step + end step}\right) \times \text{number of descending lifeline users}} \quad (1)
\]

In Eq. (1), the initial installation time, preparation step, and end step are not related to the floor where evacuation is performed, whereas the time required for the descent step increases according to the height of the floor. The evacuation time calculation model that reflects the height of evacuation is given by Eq. (2).

\[
\text{Evacuation time (seconds) = initial installation time + \left[\text{preparation step + \{(number of floors -1) \times one-floor descent step\}} + \text{end step}\right] \times \text{number of descending lifeline users}} \quad (2)
\]

When the average evacuation time obtained through the mock-up experiment was considered in Eq. (2), the result is as follows. As the time required to descend by two floors was measured in the mock-up experiment, 1/2 of the value of the descent step was considered as the time required to descend by one floor and the result is expressed by Eq. (3).

\[
\text{Evacuation time (seconds) = 60 + \left[34.2 + \{(number of floors -1) \times 4\}\right] \times \text{number of descending lifeline users}} \quad (3)
\]

In the case of the elevating evacuation equipment, no initial installation time was required, and evacuation was performed through the preparation step, descent step, and end step. In this instance, the time required for the descent step varies depending on the number of floors where evacuation is performed. Accordingly, the time required for N people to evacuate using the elevating evacuation equipment is given by Eq. (4).
Evacuation time (seconds) = \[\text{preparation step} + \{(\text{number of floors} - 1) \times \text{one-floor descent step}\} + \{(\text{number of floors} - 2) \times \text{transfer step}\} + \text{end step}\] \times \text{number of elevating evacuation equipment users} 

(4)

When the average evacuation time obtained through the mock-up experiment was considered in Eq. (4), the result is as follows. In the case of the average time required for the descent step, the average value of descent 1 and descent 2 was considered. In addition, evacuation time calculation models were derived separately for the group over the age of 60 and the group under the age of 60. The time required for the group over the age of 60 to evacuate using the elevating evacuation equipment is expressed as Eq. (5).

Evacuation time (ages over 60) (seconds) = \[17.3 + \{(\text{number of floors} - 1) \times 10.5\} + \{(\text{number of floors} - 2) \times 11.1\}\] \times \text{number of elevating evacuation equipment users} 

(5)

In addition, the time required for the group under the age of 60 to evacuate using the elevating evacuation equipment is given by Eq. (6).

Evacuation time (ages under 60) (seconds) = \[7.3 + \{(\text{number of floors} - 1) \times 9.6\} + \{(\text{number of floors} - 2) \times 6.0\}\] \times \text{number of elevating evacuation equipment users} 

(6)

5.3 Efficiency evaluation for each evacuation device

The efficiency of each evacuation device was evaluated through the derived evacuation time calculation models (equations (3), (5), and (6)) to analyze their effectiveness. Prior to the efficiency analysis for the evacuation equipment, the available safe egress time (ASET) was derived through the evacuation safety verification method (route B) presented in the notification no. 1441 and 1442 of the Ministry of Construction in Japan to calculate the time available for the selected occupants to evacuate in the event of a fire in the target site[11]. The evacuation safety verification method, which was developed in Japan, evaluates living room/floor/building evacuation safety using an engineering calculation formula for predicting the amount of smoke and the smoke layer descending time in the fire room and an engineering calculator for predicting the evacuation time based on fire cases and engineering data.

The smoke layer descending time is calculated based on the fire growth rate according to the use of the living room and the interior material type, the floor area of the living room, and the ceiling height of the living room using Eq. (7).

\[t_{\text{smoke}} (\text{living room smoke layer descending time}) = A_{\text{room}} (H_{\text{room}} - 1.8)/(V_s - V_e) \]

where

\[V_s(\text{amount of smoke}) = 9\left[\left(a_f + a_m\right)A_{\text{room}}\right]^{1/3}\left(H_{\text{room}}^{5/3} + 1.8^{5/3}\right)\]

\[A_{\text{room}} : \text{Floor area of the living room (m}^2)\]

\[H_{\text{room}} : \text{Ceiling height of the living room (m)}\]

\[a_f : \text{Fire growth rate by use}\]

\[a_m : \text{Fire growth rate by interior material}\]

\[V_e : \text{Effective smoke exhaust volume} \ (\text{m}^3/\text{min})\]

According to the conditions of the experimental site selected in this study, 200 m$^2$ was selected as the floor area of the living room. The fire growth rate by use, which is calculated according to the unit calorific value, was calculated based on the unit calorific value standard (240 MJ/m$^2$) of neighborhood facilities. In addition, the fire growth rate was set to 0.35, which is the fire growth rate of wood, considering the fire case investigation result that indicated that building interior materials were composed of wood rather than noncombustible materials. Owing to the characteristics of neighborhood facilities that there are no wide windows in narrow spaces and ventilation...
is not performed well, the effective smoke exhaust volume was not considered for the calculation. Consequently, the smoke layer descending time in the living room in the event of a fire on the corresponding floor was calculated to be 0.51 min. In other words, the time required for smoke to reach the human breathing height was observed to be only 30 s.

The evacuation efficiency of each evacuation device was analyzed by comparing the ASET derived in accordance with the evacuation safety verification method, the evacuation time calculation models for the descending lifeline and elevating evacuation equipment, and the evacuation time of an articulated ladder truck and a spiral suit derived through a previous study [4]. For application in the same environment, the evacuation time obtained from the 4th floor in the previous study was converted into the time required to evacuate using a spiral suit and an articulated ladder truck on the 3rd floor.

Preparing an articulated ladder truck for rescue required 7.8 s after it was stopped; 26.3 s were needed for it to be moved to the height of the 3rd floor and 30.2 s for it to descend. Furthermore, 5.7 s was required on average for two occupants to reach the articulated ladder truck. In the case of the spiral suit, 5 s was needed on average for occupants to prepare and 9.37 s on average to perform vertical evacuation from the height of the 4th floor. As the target site of this study has the height of the 3rd floor, the preparation time was considered as 5 s and the descent time was considered as 7.03 s for analysis.

Figure 5 shows the evacuation time derived by employing the evacuation time calculation models for the descending lifeline and elevating evacuation equipment and the evacuation time results for the articulated ladder truck and spiral suit. When the evacuation of 30 occupants was assumed, the time required was approximately 360 s for the spiral suit and approximately 1,500 s (25 min) for the elevating evacuation equipment (ages over 60). In the case of the articulated ladder truck, the evacuation time is expected to increase further because the time required for the fire rescue team to approach the site must be considered.

![Figure 5. Evacuation time for each evacuation device.](image)

According to the evacuation safety verification method, the ASET was observed to be 30 s for a neighborhood facility with a floor area of 200 m². When the number of people who can be evacuated was analyzed for each evacuation device, it was observed that two people could be evacuated by using the spiral suit and not a single person could be evacuated within 30 s by using other evacuation devices.

As the number of people who can be accommodated in a neighborhood facility with an area of 200 m² is calculated to be 66 according to the calculation method in Appendix 4 of the Enforcement Decree of the Act on Installation and Management of Firefighting Systems [12], all people except one or two persons out of 66 people...
will be affected by smoke while they evacuate using evacuation equipment. In other words, the installation of evacuation equipment currently presented based on the total floor area cannot guarantee the safety of occupants in a situation where evacuation must be performed using the evacuation equipment. It is deemed necessary to install evacuation devices considering their efficiency and capacity rather than their installation according to the total floor area.

6. Conclusion

To ensure the self-evacuation of occupants in the event of a fire, evacuation equipment installation standards have been set based on the use and total floor area of buildings. Evacuation equipment is more important in neighborhood facilities with one direct stairway, and it acts as the only means to ensure the self-evacuation of occupants in a situation where fire makes evacuation using stairs impossible. However, the NFSC of Korea does not consider the efficiency and capacity of evacuation equipment, and the number of evacuation devices to be installed is specified only according to the area of each facility. The evacuation equipment installed based on the indiscriminate legal regulation without considering evacuation efficiency cannot guarantee the safety of occupants in the event of a fire. To address this problem, evacuation efficiency should be analyzed by performing mock-up experiments, and evacuation devices must be installed by reflecting their evacuation efficiency.

Therefore, in this study, evacuation experiments were performed to analyze the evacuation efficiency of a descending lifeline and elevating evacuation equipment, and evacuation time calculation models for these devices were proposed based on the experiment results. In addition, the smoke layer descending time was derived in a floor area of 200 m² with one direct stairway, and the safety and efficiency of the evacuation equipment were verified by applying the results of a previous study and the results of mock-up experiments.

1) Based on the mock-up experiment results, evacuation time calculation models were developed for the descending lifeline and elevating evacuation equipment (equations (3), (5), and (6)).

2) When the evacuation efficiency of each evacuation device was analyzed based on the previous study and mock-up experiments, the spiral suit had the highest efficiency and the efficiency was the lowest when people aged over 60 years were evacuated using the elevating evacuation equipment.

3) The smoke layer descending time of a neighborhood facility with a floor area of 200 m² was observed to be 30 s. This value was compared with the evacuation time of each evacuation device, revealing that two people were evacuated by using the spiral suit and evacuation was impossible in the case of using other evacuation devices. In other words, efficient evacuation using evacuation equipment is impossible under the current evacuation equipment installation regulations. To address this problem, installing evacuation equipment suitable for occupants and buildings by analyzing the evacuation efficiency of each evacuation device is determined to be the most important.

In this study, the evacuation efficiency of two evacuation devices was evaluated by conducting mock-up experiments, and the results were compared with the evacuation efficiency of two evacuation devices investigated in a previous study. The evacuation efficiency of the evacuation equipment was significantly different depending on the age of the user, as indicated in the experiment results for the elevating evacuation equipment. In the future, the efficiency of each evacuation device must be analyzed more precisely through mock-up experiments for various ages. In addition, studies to ensure the safety of occupants in neighborhood facilities will be conducted based on efficiency analysis considering various fire scenarios and evacuation devices.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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