

Article

Structural Performance Assessment of Sliding-Type Evacuation Ladders Under Realistic Fire Evacuation Loading Conditions

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Abstract

This study evaluates the structural performance of sliding-type evacuation ladders under realistic fire evacuation loading conditions using parametric numerical analysis. A series of finite element models was developed based on the original ladder design, and key parameters—including member thickness (1–4 mm), overlap length between modular units (40–70 mm), loading configurations, and boundary conditions at the ladder base—were systematically varied. A total of 288 numerical cases were analyzed to investigate their influence on global displacement behavior. The results indicate that a minimum member thickness of 2 mm is required to satisfy displacement-based serviceability criteria; however, this threshold may be insufficient when connection flexibility is considered. The overlap length has a more pronounced effect on structural performance for thinner members, while the loading height has a significant effect on the displacement response. In addition, the boundary condition at the ladder base plays a critical role, with vertical support conditions substantially reducing overall displacement. These findings highlight the importance of system-level structural evaluation beyond component-based testing. They also provide practical insights for improving the design criteria and installation conditions of evacuation ladders in high-rise residential buildings during fire emergencies.

Keywords: evacuation ladder; fire evacuation; structural performance; parametric analysis; boundary condition



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1. Introduction

Recent urbanization and the increasing prevalence of high-rise residential buildings have intensified the need for reliable evacuation measures during fire emergencies. In apartment buildings, however, securing conventional refuge spaces is often difficult because of plan constraints, balcony configurations, and the demand for efficient use of limited floor area. In this context, alternative evacuation facilities, such as descending escape ladders, have been adopted for their practical construction and spatial efficiency. Because these devices are directly associated with occupant survival, their structural reliability should be evaluated not only for product approval but also for life-safety performance under realistic use conditions.

In Korea, the performance of evacuation ladders is regulated by the Technical Standards for Type Approval and Product Inspection of Evacuation Ladders issued by the

Ministry of the Interior and Safety [1]. These standards define component-level performance, including tensile resistance, torsional resistance, and connection strength. However, these criteria do not adequately represent the global structural behavior of ladder systems under realistic loading conditions. Such conditions include uneven loading, varying loading heights, eccentric human positioning, and different support conditions at the base. Major steel design standards, including ANSI/AISC 360-16 and Eurocode 3 (EN 1993-1-1), mainly focus on conventional structural members. They do not explicitly address the system-level behavior of deployable evacuation devices [2,3].

Previous studies have shown that structural response is strongly influenced by load distribution and boundary conditions. For example, Guo et al. [4] investigated the progressive collapse behavior of steel frame structures considering impact effects, and Anand et al. [5] analyzed the displacement response of steel bridge systems under moving loads. Wu et al. [6] examined structural response under environmental loading, while Starossek [7] clarified the mechanisms and classification of progressive collapse. Research on moving loads has also demonstrated that structural response is highly sensitive to load position and movement. Frýba [8] established the fundamental theory of structural vibration under moving loads, and Yang et al. [9] extended this concept to vehicle–structure interaction problems. Similarly, studies on human-induced loading highlight the importance of load magnitude and position. Bachmann et al. [10] provided practical guidelines for vibration problems in structures, while Kerr and Bishop [11] experimentally evaluated human-induced loading on flexible staircases. Furthermore, Živanović et al. [12] reviewed vibration serviceability under pedestrian loading and emphasized the sensitivity of structural response to human-induced actions.

Collectively, these studies suggest that structural systems subjected to position-dependent loading cannot be adequately evaluated solely through component-level testing. Despite these advancements, research specifically focusing on evacuation ladders remains limited. Previous studies have mainly addressed the introduction and necessity of evacuation ladders in residential buildings [13], and recent work has focused on evacuation performance, such as evacuation time and user operation characteristics [14,15]. Several papers have analyzed the structural performance of the evacuation systems, including escape ladder [16], cables [17], staircases [18], and rescue platforms [19]. However, there is still a lack of studies that quantitatively evaluate evacuation ladders as structural systems under realistic loading conditions. Moreover, practical ladder systems include several uncertain design parameters that are not explicitly defined in current standards, such as member thickness, overlap length between modular units, and contact conditions at the base. These parameters can significantly influence global deformation and service-ability performance, particularly under combined loading scenarios.

Accordingly, this study aims to evaluate the structural safety of a sliding-type evacuation ladder under realistic loading conditions through parametric numerical analysis. The analysis considers variations in member thickness (1–4 mm), overlap length between units (40–70 mm), loading patterns and positions (12 cases), and boundary conditions at the ladder base (free, roller, and friction conditions). A total of 288 numerical cases are analyzed using finite element modeling to investigate the influence of these parameters on global displacement behavior. By focusing on system-level structural response rather than component-level criteria, this study seeks to identify the governing factors affecting structural performance and to provide technical evidence for improving design and performance evaluation standards for evacuation ladders in high-rise residential buildings.

2. Numerical Analysis Model

2.1. Sliding-Type Ladder Model

Figure 1 illustrates the schematic configuration and operational mechanism of the ladder system. This system serves as an emergency evacuation device for situations where escape through the main entrance is not feasible, such as during fires or other hazardous events. Specifically, the device enables occupants to safely descend from an upper residential unit to a lower-floor unit within an apartment building, as depicted in Figure 1a. The overall ladder system consists of three primary components: the ladder assembly, a storage box, and two cover doors (Figure 1b). The system is typically installed on the balcony of each residential unit. This location is selected because balcony floors are generally finished with ceramic tiles, which are noncombustible materials. In contrast, other interior spaces are commonly finished with sheet vinyl, which is more vulnerable to fire. Such installation conditions enhance the fire safety performance and accessibility of the evacuation system. Structurally, the ladder is composed of multiple modular units. Each unit consists of a single rung (lateral component) and a pair of sliding rails (vertical components). The modular configuration allows the number of units to be adjusted based on floor height, ensuring serviceability across different building configurations. The distance between rungs is 349 mm, and the length of each rung is 344 mm. The cross-sectional geometry of both the steps and the sliding rails is a hollow rectangular box. The outer dimensions are 35 mm by 23 mm for the steps and 30 mm by 23 mm for the sliding rail (Figure 1c). However, the thickness of these members is not explicitly defined in the design documentation. According to the survey of ladder installation projects, a thickness of 2 mm is typically used in practice. However, this value may be adjusted based on specific project requirements and design considerations. The technical standards [1] specify that the distance between rungs must be 250–350 mm, and that the distance between rails must be greater than 300 mm. Also, the rung width must be 14–35 mm. The model meets the basic dimensional requirements specified in the standards.

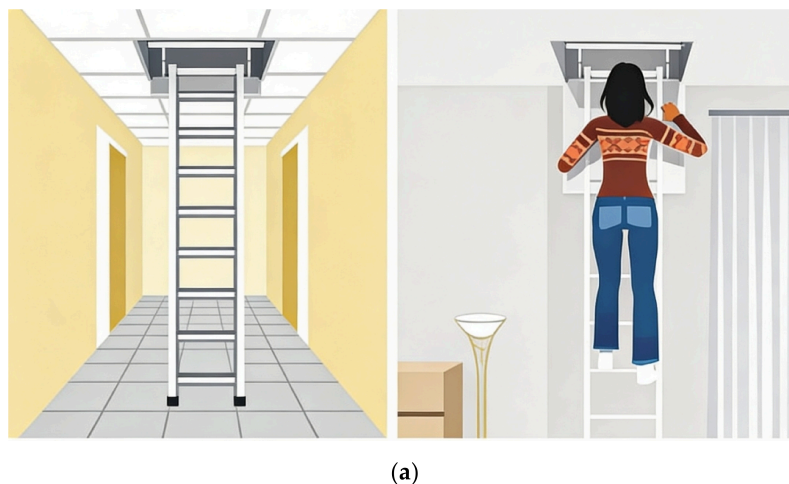


Figure 1. Cont.

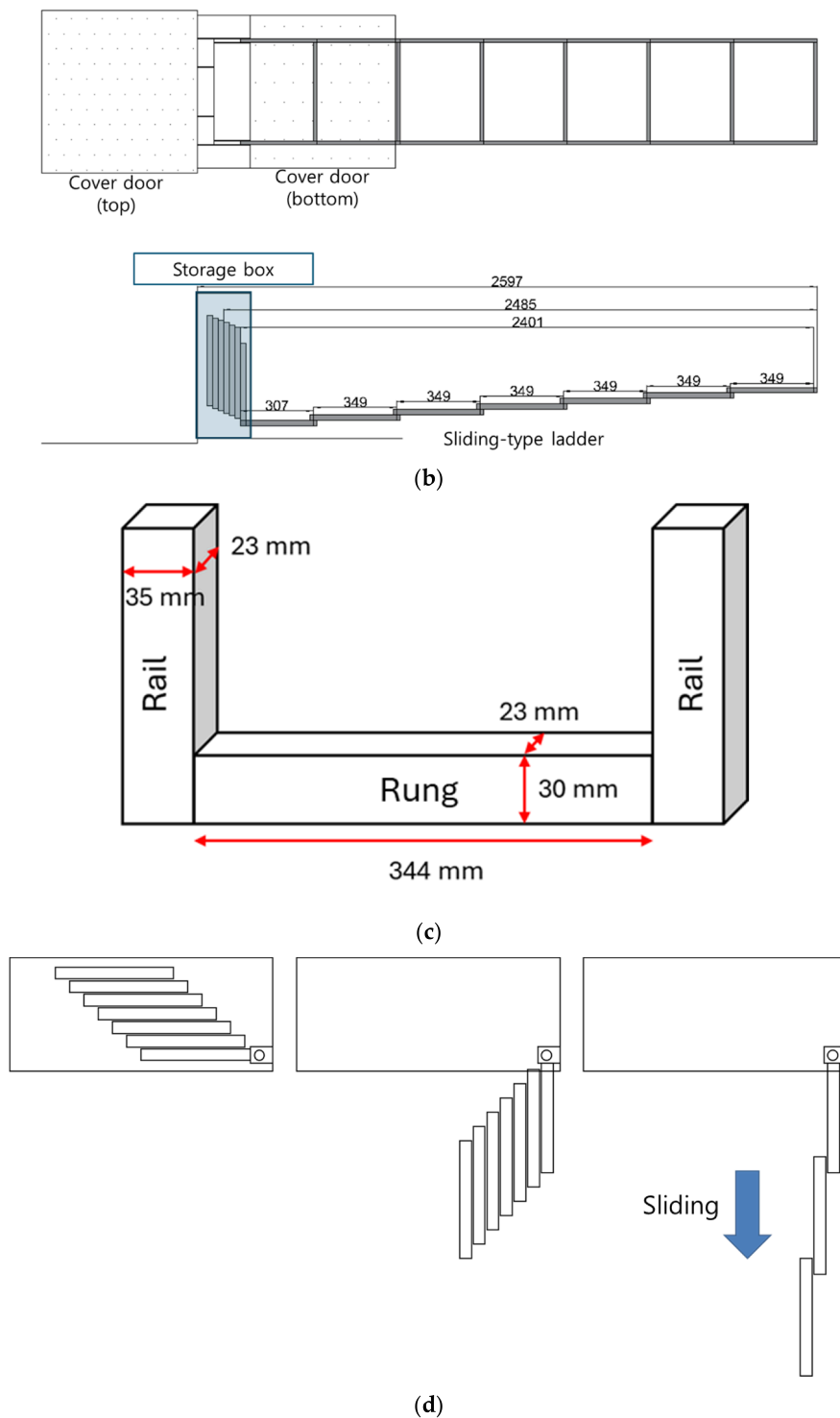


Figure 1. Sliding-type ladder: (a) Installation and usage; (b) Schematic diagram; (c) Sectional parameters of vertical and lateral components; (d) Operation mechanism.

Under normal conditions, the ladder is stored compactly within the storage box and covered by the two doors (located at the top and bottom of the floor opening). During a fire emergency, the user opens the cover doors, unfolds the upper section of the ladder, and deploys the system by sliding the units downward (Figure 1d). After full extension, each unit is locked to the adjacent upper and lower units. All units are interconnected by a wire, allowing the ladder to be manually unlocked and reset after use. Regarding material specifications, the steps are fabricated from SS400 structural steel, while the sliding rails are made of AL6061 aluminum alloy. Other components, including the storage box,

wire, cover doors, and connecting bolts, are constructed from STS304 stainless steel to ensure durability and corrosion resistance. The fundamental material properties of these components are summarized in Table 1. The standards specified these materials. Also, the standards specified basic strength and corrosion resistance requirements for materials not specified in the standard. Figure 2 represents the constructed structural model.

Table 1. Material properties of the ladder.

Name	Density (kg/m ³)	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Strength (MPa)
Aluminum 6061-T6	2700	68.9	0.33	276	310
SS400	7800	206	0.27	230	422.5
Stainless Steel 304L	8000	193	0.29	215	505

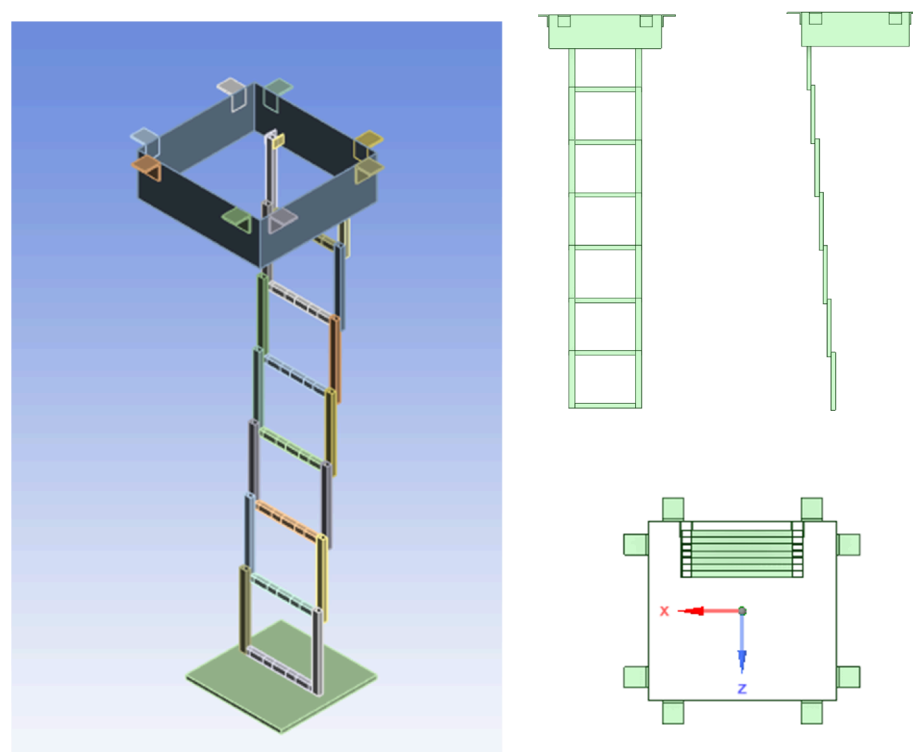


Figure 2. Structural model of sliding-type ladder.

Although most parameters and specifications are provided by the design, several parameters still need to be further defined. First, the thickness of the members is not fixed, as described earlier. This may affect sectional properties such as the second moment of area. Second, the connections between units are not fully described. The overlap length between the upper and lower rails, as well as the connection design, is not specified. Depending on the characteristics of the connection, the performance of the ladder may vary. Finally, the contact condition between the end of the ladder and the floor should be defined. If the ladder is separated from the lower floor, the end becomes a free end since there is no support. If the ladder is in contact with the floor, the end is supported in the vertical direction. The horizontal motion of the end is related to the friction between the end and the floor. To clarify these, this study numerically investigates these parameters to evaluate the structural safety of the ladder.

2.2. Test Cases

For the structural safety of evacuation ladders, the National Fire Agency of Korea has established technical standards for sliding-type escape ladders [1]. The standards specify a series of loading tests for both ladder components and the assembled system. First, the vertical components must not exhibit plastic deformation under a tensile load of 750 N (Figure 3a). Second, the lateral components must not undergo plastic deformation when a uniformly distributed load of 1500 N is applied at the center of the component over a loading width of 70 mm (Figure 3b). These tests are intended to verify the fundamental axial and bending capacities of the components. Third, the lateral components must not experience fracture or cracking under a torsional moment of 23 N·m applied at the center (Figure 3c). This loading condition simulates the torsional action induced when users place their hands or feet on the rungs. In addition, this test evaluates the integrity of the connection between the vertical and lateral components. Furthermore, the connection between the storage box and the ladder assembly must not fail (i.e., no fracture or cracking) under a vertical load equal to 1500 N multiplied by half the total length of the ladder (Figure 3d). Finally, the displacement of the ladder base must not exceed 200 mm in the horizontal direction when loaded using a standardized test apparatus representing a user (Figure 3e). The apparatus consists of two connected bars, each equipped with hook-shaped plates of 70 mm width at their ends to engage the rungs. A vertical load of 1500 N is applied downward at the midpoint of the lower bar. Unlike the component-level tests described above, this final test focuses on the serviceability of the entire structural system, which may vary depending on factors such as inter-unit connections and the contact condition between the ladder and the lower floor (Figure 3f). In addition to the structural performance requirements, the standards shortly provide the ladder performance regarding other parameters such as heat, corrosion, and paints. From the preliminary study, the first 4 test cases satisfy the acceptance criteria with a 1 mm member thickness. For the displacement test case (test 5), the ladder model provides different results regarding the structural parameters and conditions. Therefore, the test case must be further studied.

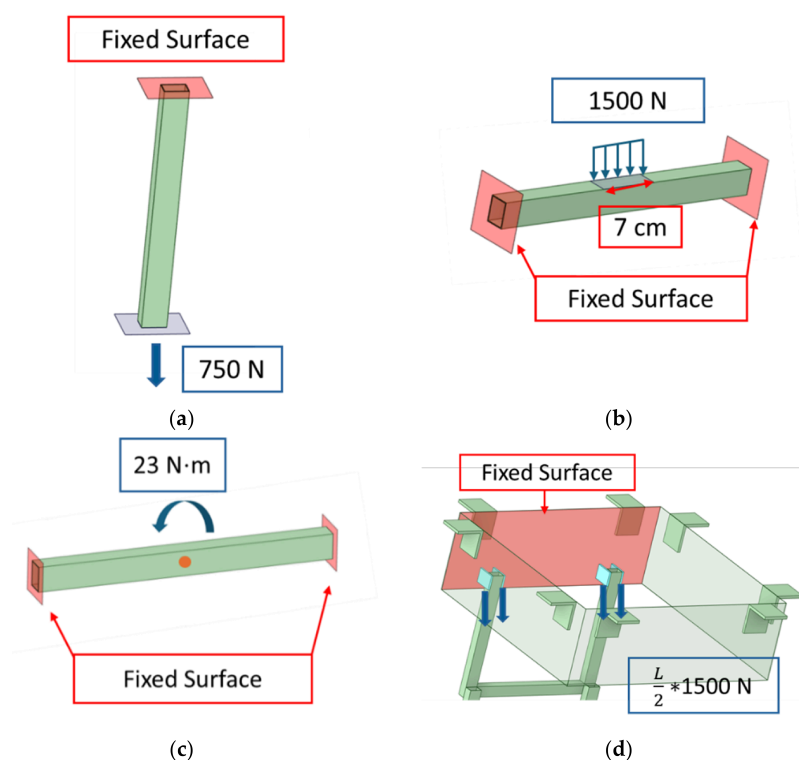


Figure 3. Cont.

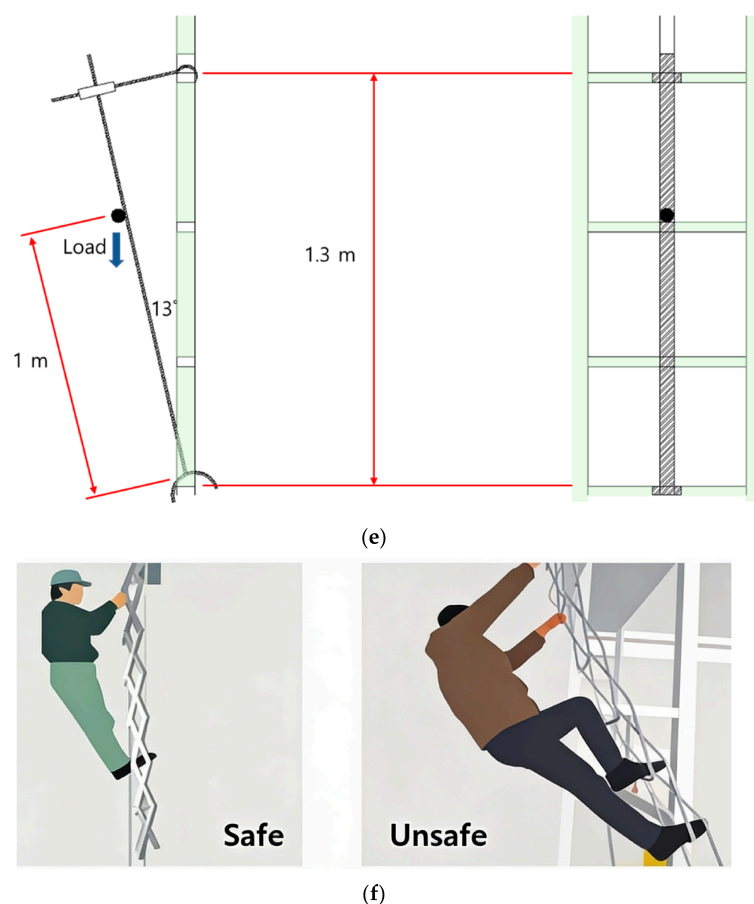


Figure 3. Test cases for escape ladders in Korea: (a) Test case 01: tension; (b) Test case 02: bending; (c) Test case 03: Torsion; (d) Test case 04: connection; (e) Test case 05: displacement test; (f) Development of Test 05.

3. Design of Parametric Study

For the numerical evaluation, this study constructed structural models with varying dimensions and applied different loading and boundary conditions. In the structural models, the member thickness and the overlap length between the rails of adjacent units were varied. The member thickness was varied from 1 to 4 mm (Figure 4a), while the outer dimensions of the members, as defined in Figure 1, were kept constant. The maximum thickness of 4 mm has been selected since the larger thickness would provide enough structural performance, while this would not provide enough inner space for wires and the locking system between units. For the overlap length, four values ranging from 40 mm to 70 mm were considered (Figure 4b). These parameters influence the sectional properties of the ladder and may affect its bending behavior. This study assumes that the bottom of the upper unit and the top of the lower unit are fully bonded, as a locking system exists between units. In addition, the hinge at the top of the ladder, which is connected to the storage box, is assumed to be fully fixed due to the locking mechanism.

Regarding loading conditions, the loading points were varied both laterally and vertically. Since the upper and lower loading positions represent the locations of the hands and feet, different configurations were considered, including cases where the hands and feet are placed on the same side or on opposite sides (left and center of Figure 4c). In addition, loading at the center of the rungs was also considered (right of Figure 4c). Furthermore, the position of the user was assumed to be either at the highest or the lowest location along the ladder (Figure 4d). Therefore, a total of 12 different loading patterns were analyzed.

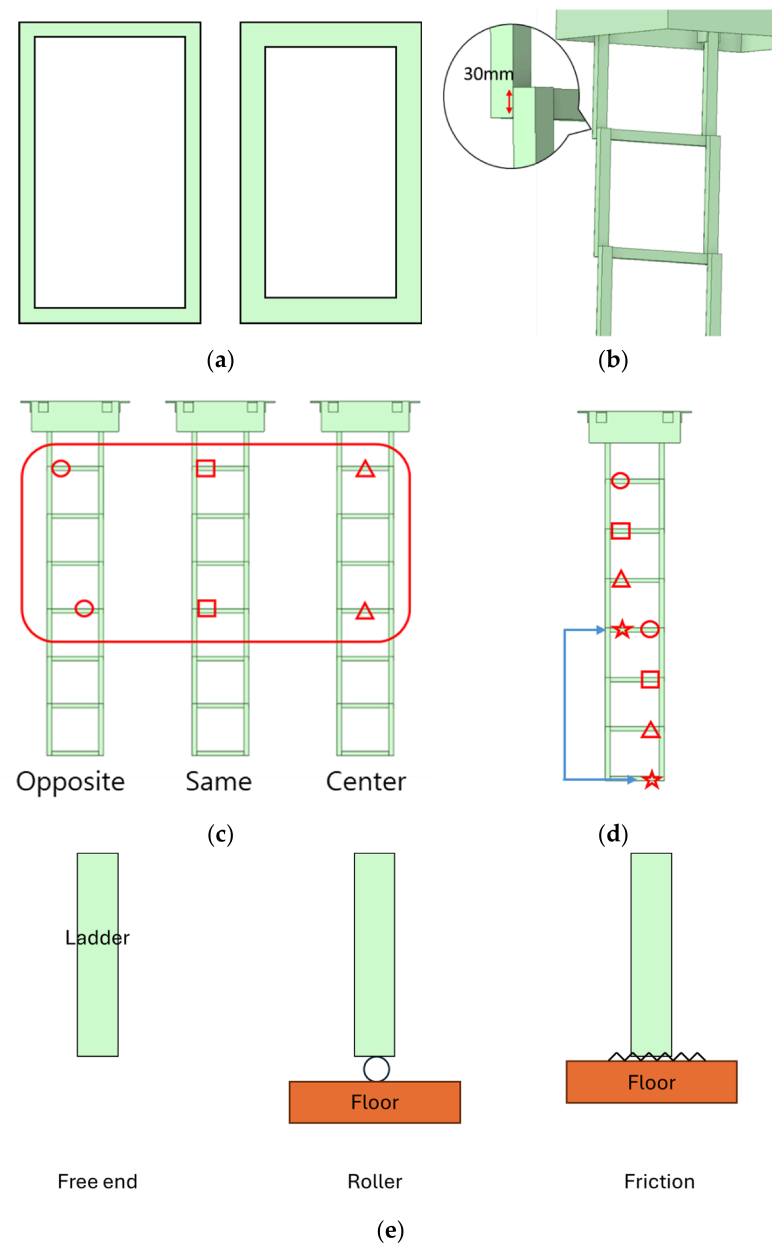


Figure 4. Variation in parameters: (a) Member thickness; (b) Overlap length; (c) Hand/foot position; (d) Vertical loading position; (e) Bottom end condition.

Finally, the boundary condition at the bottom end of the ladder was investigated. In general, the bottom end of the ladder behaves as a free end (left of Figure 4e). However, in some installation conditions, the bottom end is equipped with an anti-slip shoe and comes into contact with the floor when the ladder is fully deployed. In this case, vertical displacement at the bottom end is restrained. In addition, friction between the bottom end and the floor may affect the overall displacement response. To represent this condition, a plate was introduced at the bottom end, and a friction coefficient was defined between the bottom end and the plate. The friction coefficient was set to 0.4, considering typical friction between rubber and tile (left of Figure 4e). A frictionless condition was also considered to represent a worst-case scenario (center of Figure 4e).

Tables 2 and 3 summarize the numerical analysis cases considered in this study. The cases listed in Table 2 evaluate the effects of member thickness, overlap length, and loading patterns. A total of 192 static analysis cases were conducted. Each case is composed of different member thickness (1 to 4 mm), overlap length (40 to 70 mm), load patterns

(opposite, same, center), and loading heights (4 different heights). The cases in Table 3 investigate the effect of boundary conditions at the bottom end of the ladder. In this set, 144 cases were analyzed. Each case includes different thicknesses, loading patterns, loading heights, and boundary conditions. Twelve loading cases were considered due to the characteristics of the loading configuration. The test equipment can induce lateral forces on the connected rungs; therefore, the vertical position of the loading relative to the ladder may result in different displacement responses, even when friction is present. The number of total cases is 288 since the 48 cases (all free boundary cases) in Table 3 are already completed in Table 2 ($192 + 144 - 48 = 288$).

Table 2. Numerical analysis set for the structural model and loading pattern.

Category	Parameter	Setup
Structural Parameter	Member Thickness	1, 2, 3, 4 mm
	Overlap Length	40, 50, 60, 70 mm
Loading Condition	Load Pattern	Opposite, same, center
Boundary Condition	Loading Height	4
	Bottom-end condition	Free
Total		$4 \times 4 \times 3 \times 4 \times 1 = 192$ Cases

Table 3. Numerical analysis set for boundary conditions.

Category	Parameter	Setup
Structural Parameter	Member Thickness	1, 2, 3, 4 mm
	Overlap Length	40 mm
Loading Condition	Load Pattern	3 (Opposite, same, center)
Boundary Condition	Loading Height	4
	Bottom-end condition	Free, Roller, Friction
Total		$4 \times 1 \times 3 \times 4 \times 3 = 144$ Cases

All numerical analyses were performed using the static structural analysis solver in ANSYS Mechanical (version 2025 R2). The software is well known for structural analysis of various steel structures [19–22]. Also, the software has been used to simulate thermal effects on structures [23–25], to assess fatigue of steel structures [24,26,27], and to analyze collision effects on structures [28,29]. The storage box was modeled as a rigid body. In addition, all four outer walls were fixed, such that the storage box was assumed to be fully bonded to the floor (Figure 5a). In most cases, the storage box is well bonded to the floor by multiple anchors and does not contribute to the displacement. For loading conditions, equivalent force sets were applied instead of explicitly modeling the test equipment (Figure 5b). The equivalent vertical (240 N at the top and 1260 N at the bottom rung) and horizontal forces (260 N each) exerted on the rungs by the test apparatus were calculated and applied as distributed loads over designated areas. The top hook-shaped plate demonstrates the hand, while the bottom plate demonstrates the foot. The directions of the horizontal forces at the top and the bottom are different since the hand pulls the rung while the foot pushes it. The width of the loading area was set to 70 mm, corresponding to the width of the hook-shaped plate described previously in Figure 3e. The force set in Figure 5b has been applied at the loading area as distributed forces. Vertical forces are applied at the top of the rungs, and horizontal forces are applied at the front of the rungs. The equivalent vertical and horizontal forces exerted on the rungs by the test apparatus were calculated and applied as distributed loads over designated areas. The loading area width was set to 70 mm, corresponding to the width of the hook-shaped plate described previously. For both same-side and opposite-side loading patterns, the distance between the loading area

and the rail was set to 17 mm. A maximum mesh size of 5 mm was adopted for the finite element model. The mesh size has been selected from a preliminary study that compared the results of different mesh sizes (20, 10, 5, 2.5, and 1 mm). The 5 mm mesh size shows the same displacement characteristics as the 2.5 mm and 1 mm mesh sizes. At the bottom end, a displacement constraint was applied to restrain vertical movement, representing a roller support condition (i.e., zero friction coefficient) provided in ANSYS. This condition represents the frictionless support. For the frictional contact case, an interface condition of “adjust to touch” was assigned, and the friction coefficient of 0.4 was specified.

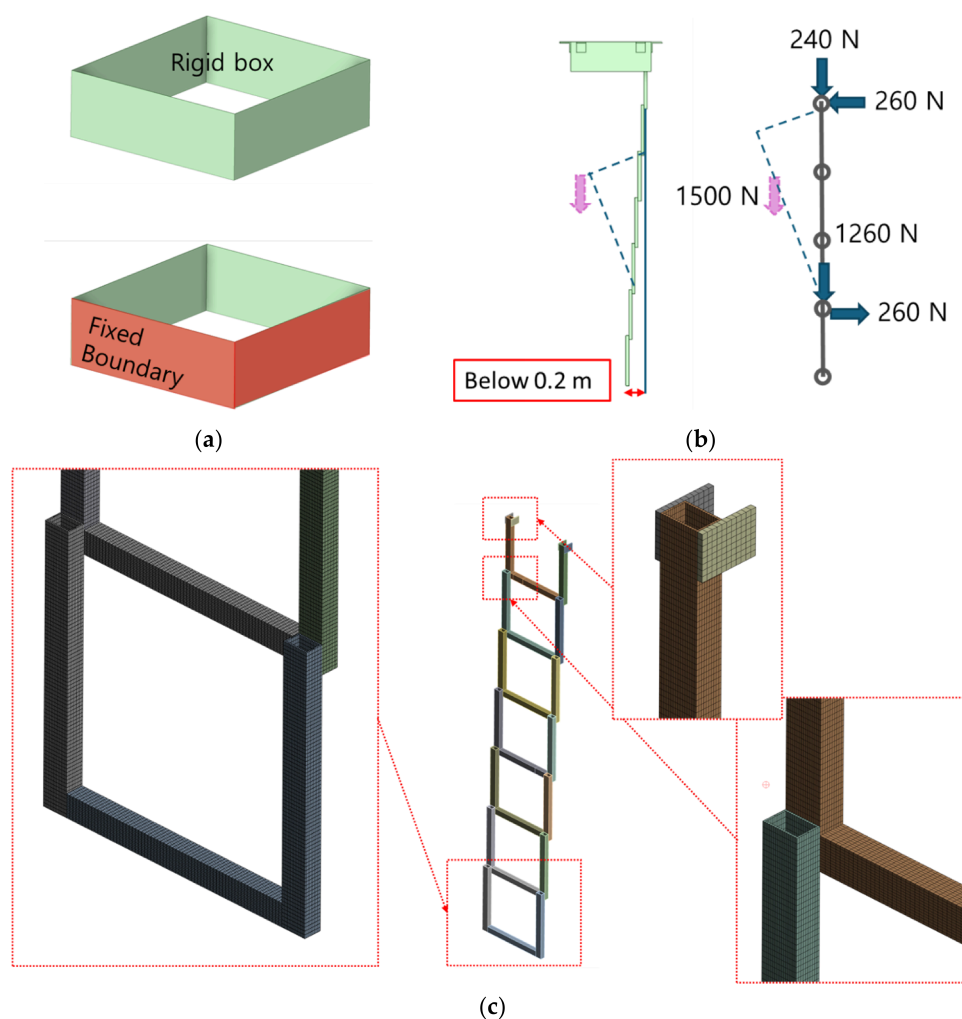


Figure 5. Numerical analysis setup: (a) Setup around box; (b) Vertical loading position; (c) Meshing.

4. Numerical Analysis Results

4.1. Structural Model and Loading Pattern

Figure 6 illustrates the displacement responses of the models with varying member thicknesses and overlap lengths. The reported displacement values correspond to the maximum values obtained from the 12 loading cases. The red dash line is the threshold, 0.2 m. As shown in the figure, all models with a member thickness of 1 mm exhibit displacements exceeding 0.2 m. In contrast, models with thicknesses of 2 mm or greater show significantly reduced displacements, generally remaining below the allowable limit. However, a thickness of 2 mm may not fully satisfy the performance criteria under realistic conditions, particularly when the assumption of fully bonded connections between units is not met. If the inter-unit connections are not perfectly bonded, additional rotational deformation may occur at the connections. For instance, assuming an additional rotation of

0.5° (0.008 rad) at each inter-unit connection, the additional displacement of approximately 63 mm may be induced. In such a case, a member thickness of 2 mm would not meet the displacement criteria, even with an overlap length of 70 mm. The maximum displacement for 3 mm and 4 mm member thicknesses is 145 mm and 113 mm, respectively. For a 3 mm thickness, the ladder would meet the criteria if the unit connections behave as assumed. If the additional rotations are generated at the connection, the ladder with a 3 mm thickness also could not meet the criteria. For a 4 mm thickness, the ladder would meet the criteria even if the additional rotations are generated at the connection. The influence of overlap length on displacement is more pronounced in models with smaller thicknesses, which is consistent with structural behavior. For a thickness of 1 mm, increasing the overlap length by 30 mm reduces the displacement by approximately 50 mm. In contrast, for a thickness of 4 mm, the same increase in overlap length results in a reduction of approximately 30 mm in displacement. For stress level, all cases show maximum stress below the yield stress.

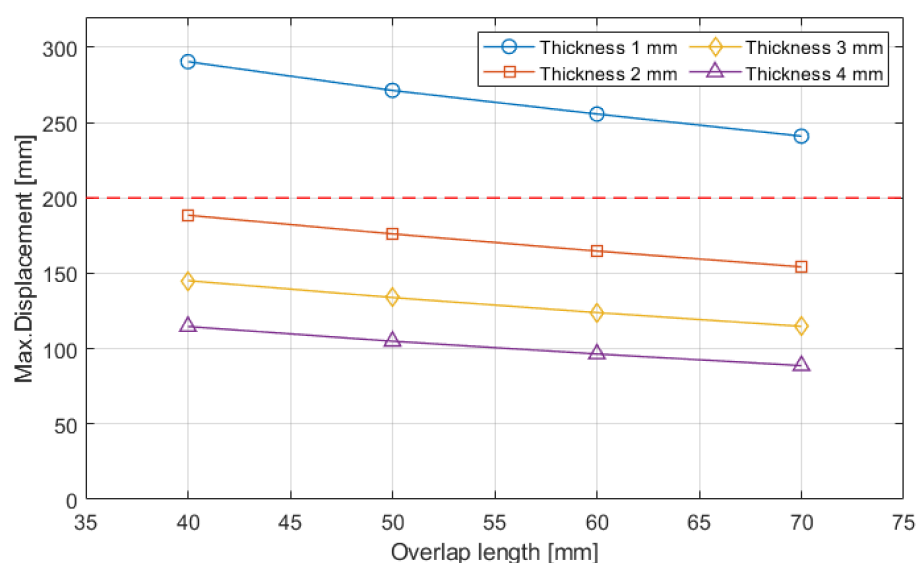


Figure 6. Maximum displacement for different overlap lengths and member thickness.

Table 4 presents the displacement responses of the models under different loading cases. The naming of each load case reflects both the loading pattern (opposite, same, and center) and the loading height (denoted by numerical indices). Cases with a member thickness of 1 mm are excluded, as all corresponding displacement values exceed 200 mm. Loading height 1 corresponds to the configuration in which the test equipment is positioned at the top rung. As shown in the table, larger displacements are observed at lower loading heights. This trend can be explained by the distribution of bending moments along the ladder. When the loads are applied at lower positions, the bending moment near the top of the ladder increases, resulting in larger overall displacement. In contrast, the ladder segments below the loading points experience relatively small deformation because the bending moment in those regions is negligible. Compared to the effect of loading height, the influence of loading pattern is relatively minor. Since the width of the ladder (i.e., the rung length plus twice the rail width) is relatively small, the additional displacement induced by torsional effects under opposite- and same-side loading is limited. Consequently, the overall displacement behavior is governed primarily by bending rather than torsion.

Table 4. Displacement of models for different thickness and overlap length (unit: mm).

Thickness (mm)		2				3				4			
Overlap (mm)		40	50	60	70	40	50	60	70	40	50	60	70
Load Cases	Opposite 1	142.3	129.9	119.0	109.3	94.6	87.4	79.6	72.6	70.5	63.6	57.8	52.7
	Opposite 2	171.8	157.7	145.2	134.0	121.4	110.4	100.8	92.3	90.7	82.0	74.6	68.0
	Opposite 3	186.3	172.4	159.9	148.6	137.4	125.8	115.6	106.3	105.5	95.9	87.6	80.2
	Opposite 4	188.5	176.1	164.7	154.3	145.1	133.9	123.9	114.8	114.7	104.9	96.5	88.8
	Same 1	141.9	129.4	118.6	108.9	96.3	87.2	79.4	72.5	70.3	63.4	57.6	52.5
	Same 2	170.4	156.4	144.0	132.8	120.6	109.6	100.1	91.6	90.2	81.5	74.2	67.6
	Same 3	183.8	170.2	157.8	146.6	136.0	124.5	114.3	105.2	104.6	95.0	86.8	79.4
	Same 4	185.0	172.9	161.7	151.5	143.1	132.0	122.2	113.2	113.4	103.7	95.3	87.7
	Center 1	140.5	128.1	117.3	107.7	95.3	86.3	78.5	71.7	69.6	62.7	57.0	51.9
	Center 2	169.1	155.2	142.8	131.6	119.6	108.7	99.2	90.8	89.5	80.8	73.5	67.0
	Center 3	182.7	169.0	156.7	145.5	135.1	123.6	113.5	104.4	103.9	94.3	86.2	78.8
	Center 4	184.0	171.9	160.8	150.5	142.3	131.2	121.4	112.4	112.7	103.1	94.7	87.1

4.2. Boundary Conditions

Figure 7 shows the maximum displacements at the bottom end of the ladder for different boundary conditions and member thicknesses. As shown in the figure, vertical restraint at the bottom end plays a critical role in reducing overall displacement. For the member thickness of 2 mm, changing the boundary condition at the bottom end from a free end to a roller support reduces the horizontal displacement by approximately 179 mm. Although the roller condition does not directly restrict horizontal movement, the corresponding horizontal displacements are significantly smaller than those observed under free-end conditions. This behavior can be attributed to the structural response of the ladder system. Based on the loading cases, the horizontal displacement of the ladder appears to be primarily governed by flexural behavior. Such behavior involves both tensile and compressive responses within the structure. The introduction of vertical restraint at the bottom end limits the tensile component of flexural deformation, thereby reducing overall displacement. In contrast, the difference in horizontal displacement between the roller and frictional boundary conditions is relatively small. This suggests that adjusting the effective ladder length to ensure contact with the floor can significantly improve the serviceability of the ladder system, while the additional effect of friction remains limited. As in the previous cases, all cases show maximum stress levels below the yield stress.

Table 5 provides the displacement at the bottom end of the ladder for various loading cases and boundary conditions. In the table, shaded cells indicate that the maximum displacement occurs at the bottom end, whereas unshaded cells indicate that the maximum displacement occurs at other locations along the ladder, typically at intermediate heights. This difference in displacement location is primarily attributed to the boundary conditions. In the case of a free end, the deflected shape of the ladder resembles that of a cantilever beam, with the maximum displacement occurring at the bottom end (Figure 8a). However, when horizontal displacement at the bottom end is restricted, and loads are applied at intermediate positions along the ladder, the deflection shape deviates from that of a classical cantilever beam (Figure 8b,c). Under these conditions, the maximum displacement tends to occur at mid-height regions rather than at the bottom end. In particular, for loading heights 1 and 2, where the loads are applied near the middle of the ladder, the deformation pattern becomes increasingly distinct from the cantilever behavior, further shifting the location of maximum displacement away from the bottom end. In the case of friction, the displacement becomes very small and even shows very small negative values. This also might be due to the bent shape of the ladder. This study measured the displacement at the left end of the bottom.

The lateral displacements for friction support are almost zero for a 2 mm member thickness. The small negative values come from the rotation of the bottom end.

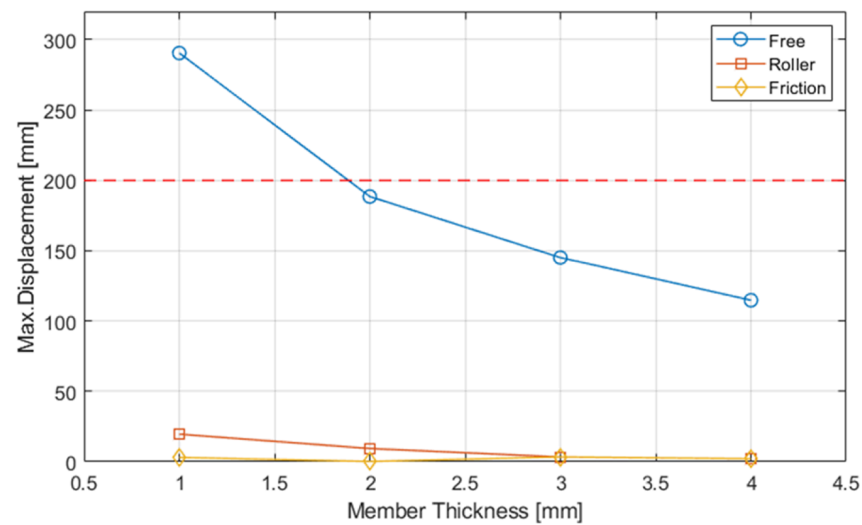


Figure 7. Maximum displacement at the bottom ends for different boundary conditions.

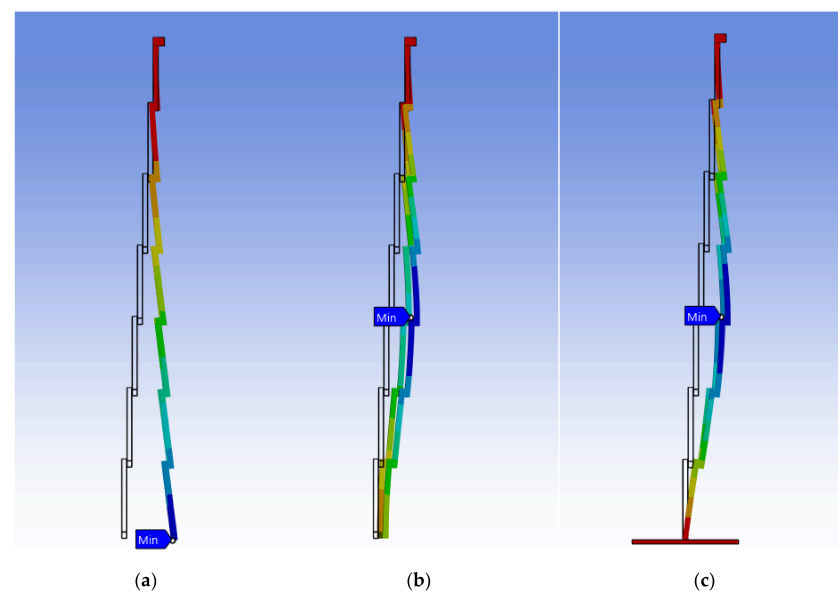


Figure 8. Bending shapes for different loading conditions: (a) Free; (b) Roller; (c) Friction.

Table 5. Displacement of models for different boundary conditions (unit: mm).

Boundary Condition		Free			Roller			Friction		
Thickness (mm)		2	3	4	2	3	4	2	3	4
Load Cases	Opposite 1	142.3	94.6	70.5	4.52	2.30	1.41	−0.02	2.33	1.42
	Opposite 2	171.8	121.4	90.7	5.17	2.79	1.75	−0.02	2.82	1.76
	Opposite 3	186.3	137.4	105.5	5.95	3.22	2.02	0.01	3.25	2.04
	Opposite 4	188.5	145.1	114.7	6.33	3.39	2.12	0.20	3.41	2.14
	Same 1	141.9	96.3	70.3	4.18	2.10	1.27	−0.01	2.13	1.28
	Same 2	170.4	120.6	90.2	4.17	2.23	1.38	−0.01	2.25	1.39
	Same 3	183.8	136.0	104.6	4.29	2.28	1.41	0.00	2.30	1.43
	Same 4	185.0	143.1	113.4	3.93	2.05	1.26	0.63	2.07	1.28
	Center 1	140.5	95.3	69.6	9.39	1.52	0.91	−0.01	1.55	0.92
	Center 2	169.1	119.6	89.5	3.02	1.63	1.01	0.00	1.64	1.02
	Center 3	182.7	135.1	103.9	3.10	1.67	1.03	0.00	1.69	1.05
	Center 4	184.0	142.3	112.7	2.87	1.51	0.92	0.10	1.52	0.94

5. Conclusions

This study evaluated the structural performance of the sliding-type escape ladder using numerical analysis. Based on the design, a set of numerical ladder models has been created. The parameters that would be changed by project conditions, the member thickness, overlap length, and boundary conditions, have been modified in these models. The structural performance of the models has been analyzed numerically. Under the ideal bonded connection assumption, a thickness of 2 mm can satisfy the displacement threshold; however, under realistic flexible connection conditions, thicker members or enhanced connection designs may be required. When the member thickness becomes 4 mm, the displacement becomes below 60% of the threshold. When the additional rotational angle is provided at the joints, a thickness of more than 2 mm would be required. The contact status between the ladder bottom and the floor could change the serviceability of the ladder. When the bottom end of the ladder is restrained vertically, the displacement becomes below 10 mm even if the horizontal friction is zero. The contact between the ladder and the floor would improve the serviceability of the ladder. These findings might be used for the design modification (e.g., size of anti-slip shoes) and the manufacturing of the ladders for the future/existing apartments.

The following limits must be improved in future studies. First, the detailed modeling of the connection parts is required. In this study, the inter-unit connection is assumed to provide the same performance as overlapped rails. Although the locking system holds the units after the deploy, the bending performance of the connection must be further defined. To develop a proper inter-unit connection model, the experiment will be performed as the next step of the research project. Based on the experiment, the connection model with a set of rotational springs and translational springs will be designed. The spring model would provide the bending properties of the ladder more accurately. Also, the connection between the top unit and the box must be numerically/experimentally studied further. In addition to connections, the performance of ladders for various situations must be studied. In case of fire, the material properties and the structural performance of the ladder could be affected by the heat. Also, the vibration due to earthquakes and high-speed wind in tall apartments (40 or more stories) would affect the ladder during usage. Furthermore, the characteristics of human-induced loads must be considered carefully. Depending on the situation, the human-induced loads could be applied to the ladder as impact loading. In case of an urgent situation, loads of 2 persons could be applied to the ladder. Finally, the future study must include the stress level at the system level test of the ladder. The research project is going to evaluate various types of ladders. Although this ladder model shows stress levels under the yield stress for all test cases, the clarification of stress levels for other ladders must be evaluated, and a revision of codes regarding this is to be studied. In conclusion, the overall performance of the ladder system under possible conditions must be studied.

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