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Research Article

Optimized Design of Safety Boards with Adjustable Spacing for Subway Platforms

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ABSTRACT

Introduction: The domestic subway industry has introduced various policies and facilities through a steady interest in safety facilities as an effort to reduce accidents. Consequently, safety facilities, such as platform screen doors and wheelchair elevators, are currently installed in subway stations. However, according to the Ministry of Land, Infrastructure, and Transport, an average of 65 trip accidents continued to occur annually. Tripping accidents in the gap between the train door and platform continue to occur because of problems with the platform structure and the occurrence of steps.

Objectives: The purpose of this study is to analyze the physical properties of safety boards to select a basic design and optimize it.

Methods: We analyzed of the internal crystal structure according to the material, material surface composition elements, and material tensile strengths. Based on these analyses, we conducted the following sub-studies: 1) Understanding the operating status by searching and organizing the latest domestic data installed and operated on the platform. 2) Analysis of the operating principles of existing safety steps and identification of the current status based on domestic patent searches for fixed, sliding, and foldable safety steps. 3) Analysis of the limitations of the existing safety boards. In other words, because safety board installation is highly expensive, it is difficult to install them at all stations. Therefore, by analyzing the advantages and disadvantages of the three methods, we conducted a structural analysis of the adjustable-interval safety step platform safety board and optimized its design.

Results: Considering the limitations and problems of existing safety steps, new ideas were proposed and the optimal safety step was selected through comparative analysis. In addition, referring to the platform safety step standards, the maximum allowable vertical distribution load of the frame was set to be 1,000 kgf or more, and the maximum allowable vertical distribution load of the movable step was set to be 500 kgf or more. After creating the basic model, the design was changed by changing the number of supports and balls.

Conclusions: The purpose of this design is to consider safety while supplementing the economic efficiency, which is the disadvantage of the existing safety steps currently installed. It can be installed at different intervals for each platform, and it was designed with safety as the top priority, preventing unexpected collisions and being safe even under high loads. In order to verify safety under load, the optimal design was selected through a comparison of deformation values between models during the ANSYS analysis process.

Keywords: Design Process, Finite Element Analysis, Neural Network, Safety Board, Structural Analysis

I. INTRODUCTION

Domestic subways have introduced various policies and facilities through a steady interest in safety facilities in an effort to reduce accidents. Consequently, safety facilities, such as platform screen doors and wheelchair elevators, have been installed in subway stations. However, according to the Ministry of Land, Infrastructure, and Transport more than 65 tripping accidents occur on average each year despite these efforts. Because of problems with the platform structure and the occurrence of steps, accidents continue to occur while people are travelling through the gap between the train door and platform. Accordingly, opinions on safety steps between platforms and trains have been raised constantly. Table 1 lists the stations at which safety steps are currently installed according to the Korea Railroad Corporation. Fig. 1 shows the gap between the subway platform and train [1,2].

Table 1: The number of installations of safety board [1]

Route (Line)	No. of fixed installation stations	Fixed quantity	No. of automated installation stations	Automatic quantity
Gyeongbu	37	4,210	2	110
Gyeongin	21	2,372	1	80
Ilsan	10	748	1	40
Gwacheon	-	-	9	631
Ansan	-	-	13	1,247
Gyeongui-Jungang	-	-	22	2,064
Jungang	20	1,755	-	-
Bundang	35	955	-	-
Gyeongchun	21	1,644	-	-
Mangu	3	416	-	-

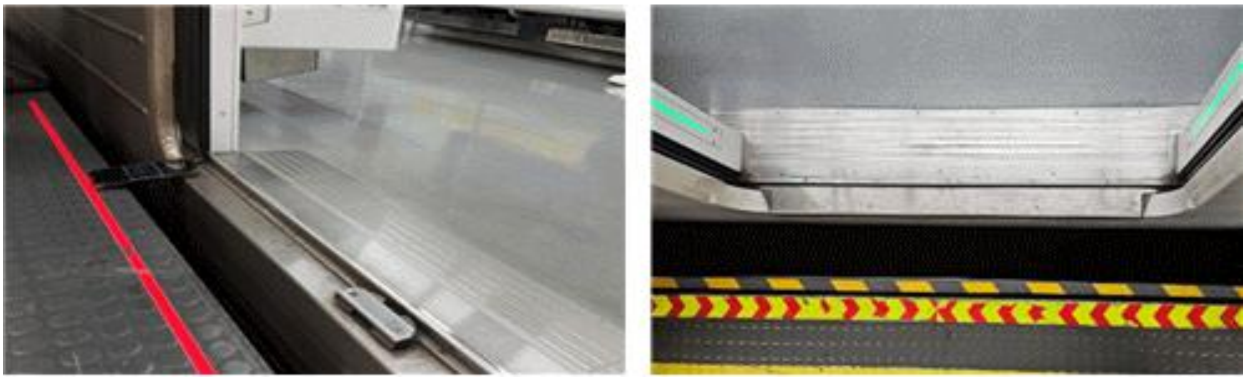

Figure 1: The gap between the subway platform and the train [2]

According to the data on ‘Subway tripping accidents in the past 5 years (including platform trips and wheelchair accidents)’ released by Seoul Metro, there were 104, 96, and 76 cases in 2020, 2021, and 2022, respectively. The most recent related case occurred during a protest by the National Coalition for the Elimination of Discrimination against Persons with Disabilities on their way to work, which has been ongoing since December last year. During the protest, the right leg of a person with a physical disability was caught in the gap between the platform and the train while getting off the subway in a wheelchair. The main goals of this protest are ‘fulfilling the promise to declare the right to deinstitutionalization for persons with disabilities’ and ‘promoting the right to mobility for persons with disabilities.’ In addition, the need for safety board is being emphasized [3].

On some platforms with safety boards installed, there have been accidents in which the steps malfunctioned owing to internal component problems. On January 14, 2020, an accident occurred at the Gimpo Airport Station on Line 5, where a train collided with a safety step. Consequently, the plan of Seoul City to install 1,300 safety steps in subway stations by 2020 was put on hold because of the safety issues pointed out by the Board of Audit and Inspection .

The purpose of this study is to suggest ways to improve the existing safety platform problem and reduce the risk of such accidents. The currently installed safety platforms can be largely classified into three types. By examining the operating method of each type, their shortcomings are detailed to suggest ideas for new safety platforms and conduct design research.

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II. LITERATURE REWIEW

2.1 Platform spacing standards and their operating status

According to the current standards of the Ministry of Land, Infrastructure, and Transport, safety stairs must be installed on curved platforms where the gap between the train and platform is 10 cm or wider. Looking at the platforms identified thus far, out of 18,856 platforms in 268 stations for which the corporation is not responsible, 3,607 platforms in 151 stations have gaps of 10 cm or wider. According to data released by the transportation corporation, the widest gap between platform and train is 28 cm, which occurs at the Seongshin Women's University Station on Line 4. Furthermore, more than 20% of the identified platforms have gaps of 20 cm or wider.

The data on the platform ratio where foot-slip accidents occur reveals that the probability of foot-slip accidents increases with the gap width. The gaps on the platforms where foot-slip accidents occurred four and three times were wider than 10 cm, and approximately 90% of the platforms where foot-slip accidents occurred were wider than 20 cm. Based on these data, the presence of a safety board is critical when the gap between platforms is wider than 10 cm. Moreover, because complaints about gaps on platforms are continuously being raised, specific alternatives become indispensable.

2.2 Operating principle of the existing safety boards

Currently, some subway platforms have safety steps that operate in various ways. There are three main types of safety board: fixed safety board, sliding safety board, and folding safety board. The operating principles of each safety board are as follows [4-8].

1) Fixed safety board

As shown in Fig. 2, fixed safety board are those that are installed on the side of a platform with rubber material to act as a step. In the case of rubber steps, they are the simplest of the three methods, as they only have rubber attached without any special function.

2) Sliding safety board

As shown in Fig. 3, the sliding safety step is installed inside the platform, and is a safety step that fills the gap between the subway and the platform by pushing the sliding safety step out through the drive motor and gear. It is composed of a drive motor, drive gear, drive-guide arm, hinge, step plate, and torque clutch.

3) Folding safety board

As shown in Fig. 4, a foldable safety board moves up and down with a signal linked to the subway. When the subway train arrives, the sensor calculates its height and outputs the corresponding signal. As a result, the foldable safety step rotates. Its angle of rotation increases with the output signal.

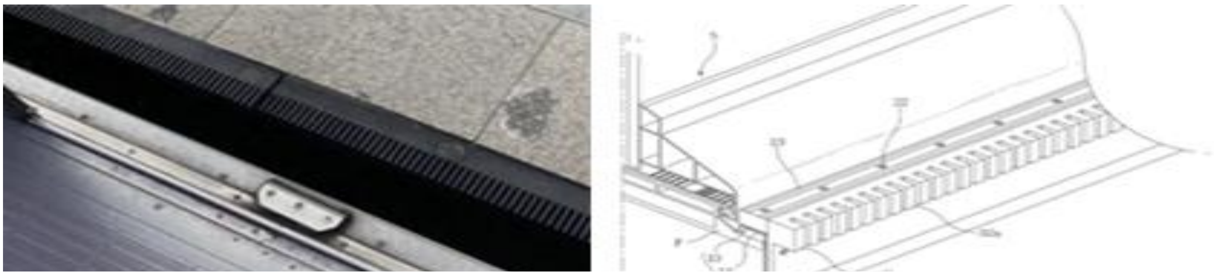


Figure 2: Image and design layout of a fixed safety board [5]

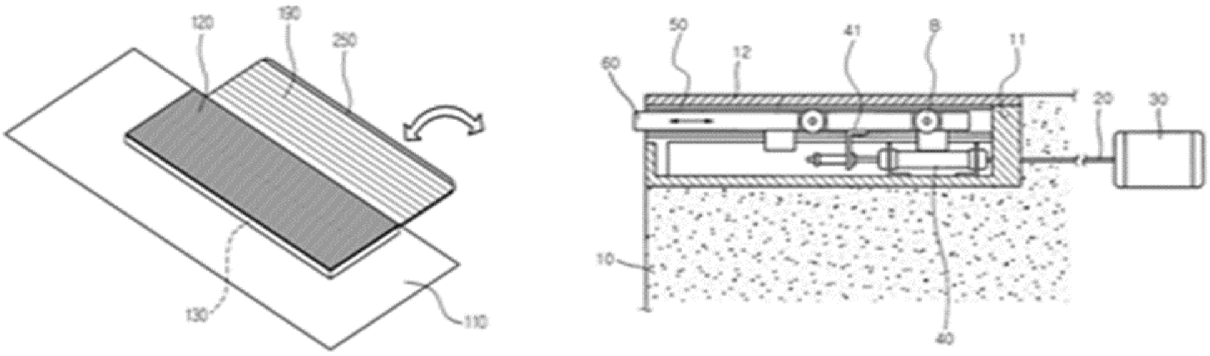


Figure 3: Desing of a sliding safety board [5]

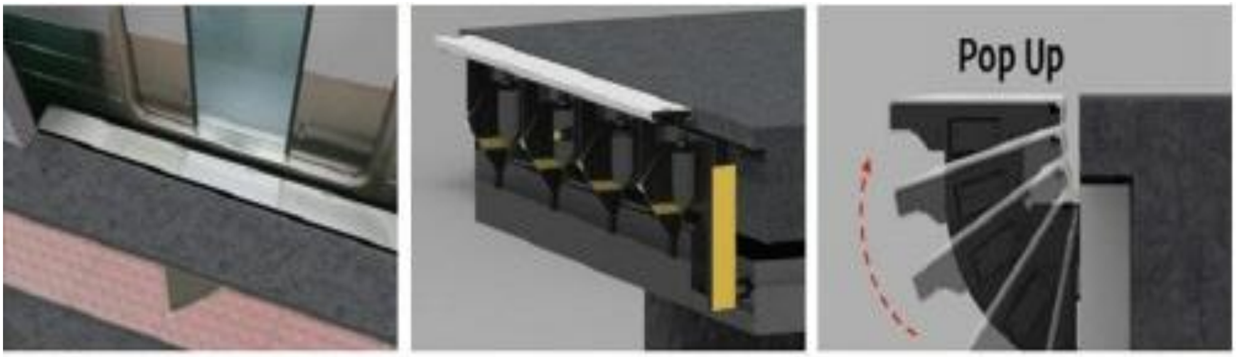


Figure 4: Image showing design of a folding safety board [3]

2.3 Limitations of existing safety boards

Currently, no subway safety steps have been installed since 2018. This is due to unreasonable business promotion, revision of promotion plans that do not consider the site, criticism from the Board of Audit and Inspection, and company abandonment. The biggest problem is the budget because the installation of safety steps at stations is highly expensive. The price of safety steps currently installed by Seoul Metro is KRW 15 million per unit, which adds up to approximately KRW 300–400 million per station. If these steps are installed at all stations with gaps of 10 cm or more, the total amount is estimated to reach KRW 54 billion. Considering that the national budget for safety in 2022 is KRW 22 trillion won, KRW 54 billion is a significant amount, increasing the difficulty in installing safety steps at all stations [9].

Furthermore, folding safety boards introduce a problem that accidents with trains can occur because the workers must enter the platform to perform construction work during installation. Whereas, in the case of the sliding type boards, the step must be inserted inside the platform, increasing construction costs. Moreover, they introduce a problem that the final board and train levels can be different. Additionally, there are numerous problems and risks, incuding as maintenance and repair of the installed steps, damage to the subway train caused if the step does not fold, and the step process, owing to the difference in the size and shape of the car for each platform.

III. METHODOLOGY

The space-adjustable safety board proposed in this study consists of a first- and second-stage steps load support, and collision prevention plate. Its operating principle is illustrated in Fig. 5. The first-stage step is fixed and always remains in an unfolded state. When installed at different intervals on each platform, the length of the second-stage step can be organically adjusted according to the angle of support by adjusting the spring. As the support is folded, the ball moves along the straight groove dug in the second-stage step, drawing it between the first-stage steps similar to a drawer along the movement of the ball, thereby adjusting its length. To prepare for an unexpected electric vehicle collision, a structure was designed that connected a collision prevention plate and load support with a bar. When the electric vehicle and the collision prevention plate collide, the support plates fold at the same angle as the collision prevention plate, preventing collisions between the electric vehicle and the step. After the electric vehicle passes, the support returns to its original angle through a spring mechanism, and the second-stage step regains its original state.

The proposed space-adjustable safety board can prevent collisions by using a collision-prevention plate. The existing subway safety boards have a high risk of collision accidents due to malfunction and collision risk due to left-right shaking that occurs during subway operations, especially on curved sections. Therefore, although a space-adjustable safety board is primarily designed to prevent collisions, it can reduce the damage caused when a collision occurs.

Existing sliding or folding safety boards incur energy costs owing to the power consumption during operation. As a solution, the space-adjustable safety board was designed using a fixed safety step, reducing energy costs because no power is required for its operation.

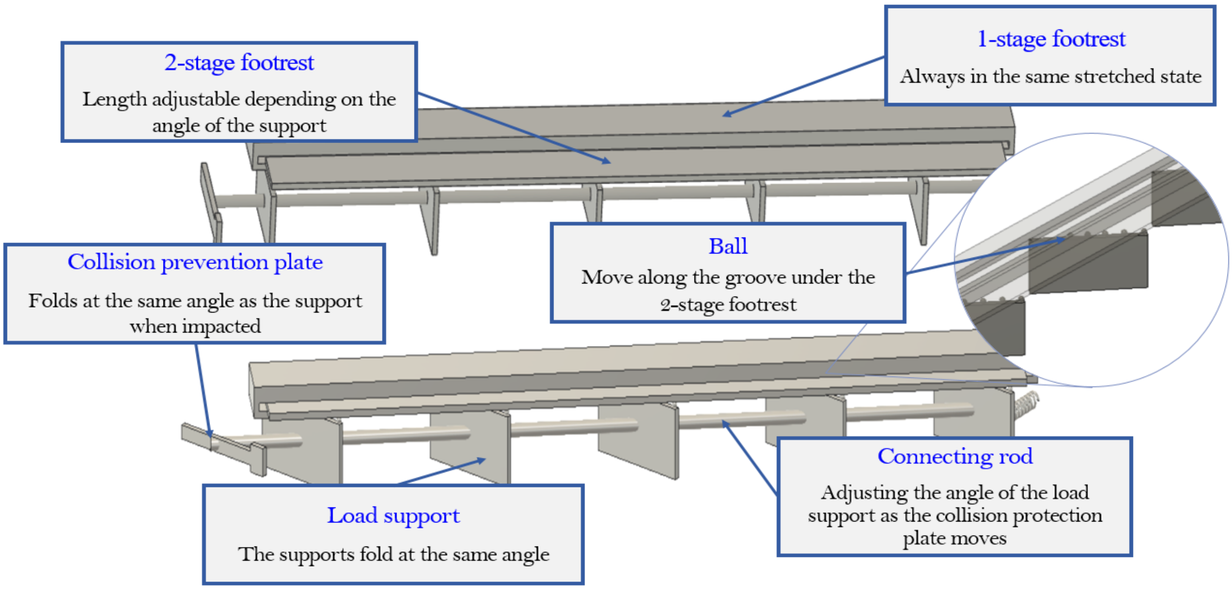


Figure 5: Design of a spacing adjustable safety board

Existing sliding safety boards and embedded folding safety boards are highly expensive because they must be installed after destroying the concrete of the platform. In addition, because the folding safety board does not have adjustable length, it must be manufactured specifically for each platform to fit the spacing. On the other hand, the spacing-adjustable safety board design reduces installation costs at it only needs to be attached to the platform, keeping the concrete intact. These characteristics enable a standardized process for their factory production owing to the design structure that supports length adjustment, thereby reducing manufacturing costs.

Furthermore, because platform safety board installations carry a high accidental risk due to subway operations, the construction work must be performed early in the morning when the subway is non-operational. Thus, the installation time of safety boards must be shortened. As a solution, the proposed spacing-adjustable safety board can be installed by attaching it to the platform without destroying the concrete, shortening its installation period compared to that of existing safety boards.

3.1 Material selection through tensile testing and Energy-Dispersive Spectrometer (EDS) analysis

In this paper, we aimed to design a new space-adjustable safety platform by pointing out the limitations of the three existing safety platforms and to select a material with excellent corrosion resistance and appropriate strength by using tensile tests and SEM equipment as a basic study. To analyze SS-Curve and yield stress data through tensile tests, experiments were conducted on five materials, including STS304L, STS316L, STS630, Monel400, and Hasteloy-C, using a UTM machine as shown in Fig. 6. Additionally, in order to analyze the components, EDS analysis was performed on each material using the equipment shown in Fig. 7.

Figure 6 UTM equipment [1]

Figure 7 EDS analysis equipment [1]

3.2 FEA setup

Because the current study aims to improve the existing safety platforms in terms of their purpose and use, in this section, we presented various ideas to complement the limitations of the existing safety platforms. Subsequently, each idea is evaluated for safety, economic feasibility, and social aspects according to the appropriate criteria, and the optimal structure is selected through comparative analysis. Next, the basic form and maximum load of the platform were analyzed to calculate the maximum load that the chosen safety platform and support must withstand. In addition, the specific form and thickness of the platform were calculated to obtain their theoretical values. After selecting the basic values based on these results, a structural analysis was performed. A structure that can ensure driving stability by deforming and adjusting each part was analyzed. In addition, materials were selected to ensure safety even in the event of a collision, and the final design plan was determined based on the derived results. Finally, comprehensive safety and economic feasibility were evaluated by manufacturing a prototype.

3.3 Design process

This method consists of three modules, as shown in Fig. 8. First, an FE analysis system was used to perform numerous finite element analyses to prepare the training and test data for the neural network. These values were the combined physical values that compared the calculation results with the assumed design variables. Subsequently, the neural network was trained using the training data. Here, design variables including the numbers of supports and balls were provided to the input units of the network, and physical values including the calculated deformation values were displayed as teacher signals at the output units. The learning algorithm used in this study was a back propagation algorithm [10].

The final design was selected by applying neural network theory using as input variables the number of supports supporting the safety board, the material of the safety board, and the deformation amount according to the number of balls connecting the safety board and the supports.

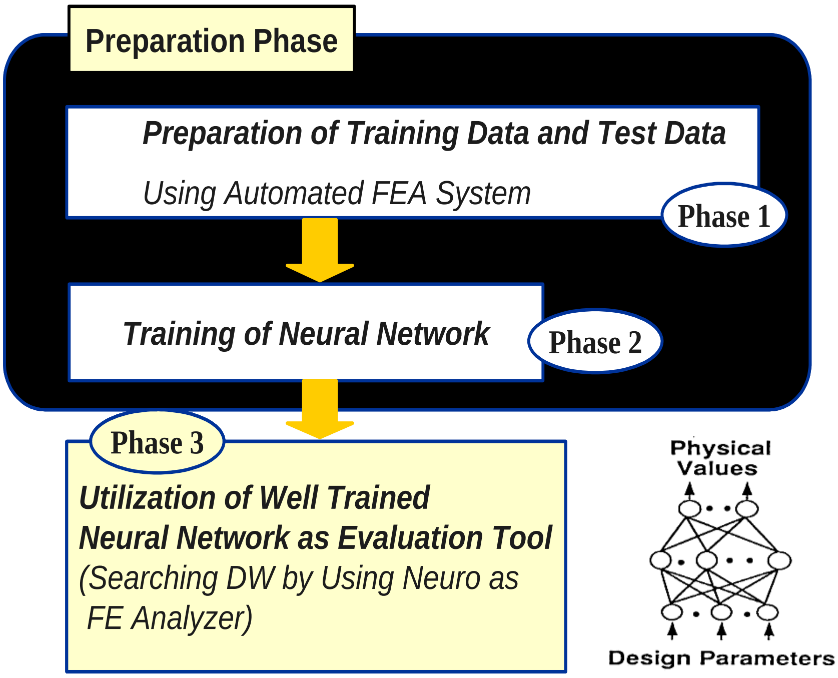


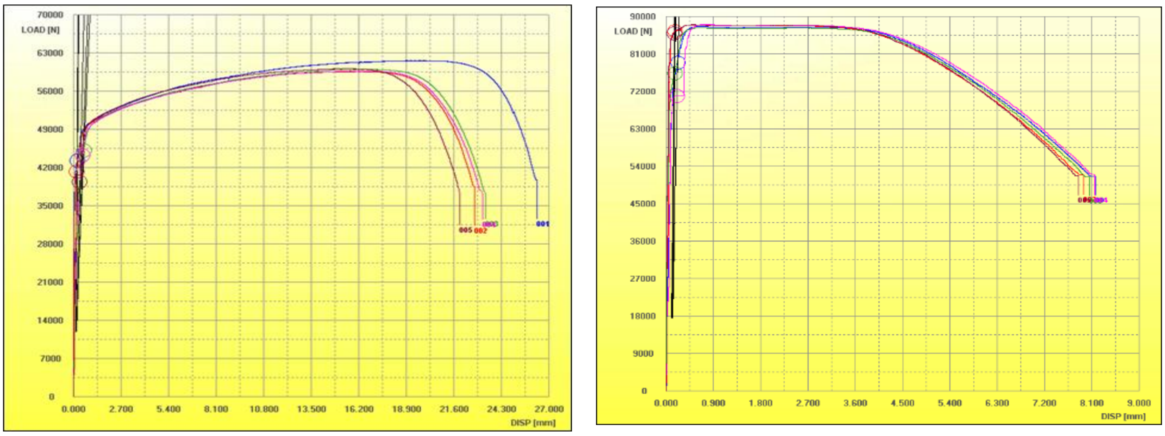
Figure 8: Procedure for final design search using a neural network

IV. RESULTS

4.1 Material test results

For example, the tensile test results of STS304L and STS630 are shown in Fig. 9. Also, the comprehensive experimental results for the five materials are shown in Table 2. The tensile test results showed that STS630 had the highest tensile strength and yield strength.

As a result of EDS analysis using SEM, the distribution ratio of elements distributed on the surface of the corresponding materials could be confirmed, and the corrosion resistance of the corresponding materials was evaluated through this. As an example, the analysis results for STS304L and STS630 materials are shown in Fig. 10.

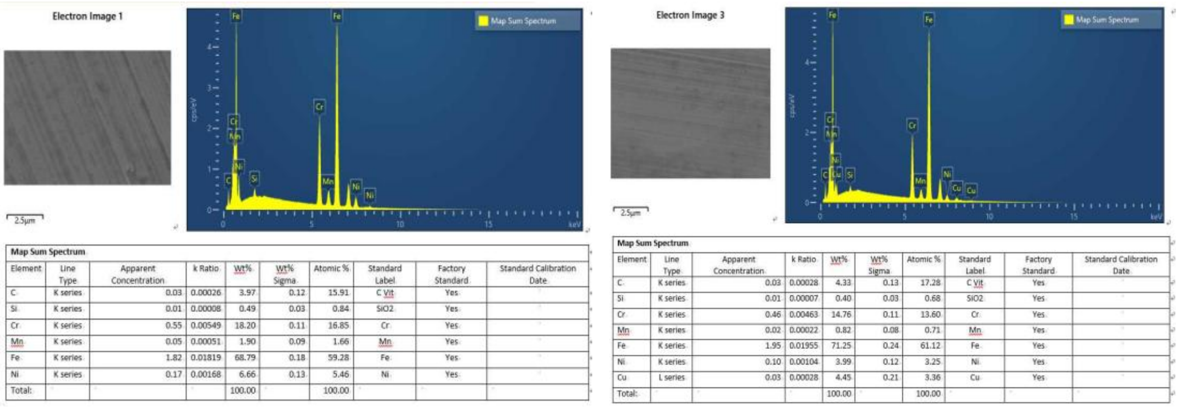


(a) STS304L (b) STS630

Figure 9: Result of stress-strain curve

Table 2: Results of tensile test

Materials	Tensile Strength (MPa)	Yield Strength (MPa)
STS304L	766.31	542.77
STS316L	674.05	509.74
STS630	1117.6	1014.8
Monel400	565.78	361.03
Hasteloy-C	811.38	490.13



Map Sum Spectrum

Element	Line Type	Apparent Concentration	k Ratio	Wt%	Wt% Sigma	Atomic %	Standard Label	Factory Standard	Standard Calibration Date
C	K series	0.03	0.00026	3.97	0.12	15.91	C Vit	Yes	
Si	K series	0.01	0.00008	0.49	0.03	0.84	SiO2	Yes	
Cr	K series	0.55	0.00549	18.20	0.11	16.85	Cr	Yes	
Mn	K series	0.05	0.00051	1.90	0.09	1.66	Mn	Yes	
Fe	K series	1.82	0.01819	68.79	0.18	59.28	Fe	Yes	
Ni	K series	0.17	0.00168	6.66	0.13	5.46	Ni	Yes	
Total:				100.00		100.00			

Map Sum Spectrum

Element	Line Type	Apparent Concentration	k Ratio	Wt%	Wt% Sigma	Atomic %	Standard Label	Factory Standard	Standard Calibration Date
C	K series	0.03	0.00028	4.33	0.13	17.28	C Vit	Yes	
Si	K series	0.01	0.00007	0.40	0.03	0.68	SiO2	Yes	
Cr	K series	0.46	0.00463	14.76	0.11	13.60	Cr	Yes	
Mn	K series	0.02	0.00022	0.82	0.08	0.71	Mn	Yes	
Fe	K series	1.95	0.01955	71.25	0.24	61.12	Fe	Yes	
Ni	K series	0.10	0.00104	3.99	0.12	3.25	Ni	Yes	
Cu	L series	0.03	0.00028	4.45	0.21	3.36	Cu	Yes	
Total:				100.00		100.00			

(a) STS304L (b) STS630

Figure 10: EDS analysis result

As a basic study for designing automatic safety board for subway platforms, this study analyzed the material properties according to the safety step material to be selected. The tensile test results confirmed that the strength was measured to be superior to the standard value for each material. In addition, when comparing the simple yield strength, the best material was determined to be STS630. When comprehensively judging, STS630 has excellent corrosion resistance and appropriate strength, so it is intended to be selected as the main material to design the safety step.

4.2 Deformation analysis results

Fig. 11 is a 3D model of a safety board based on what was explained in Chapter 3. Using this 3D modeling method, we aim to examine the change in deformation by varying the number of supports and balls.

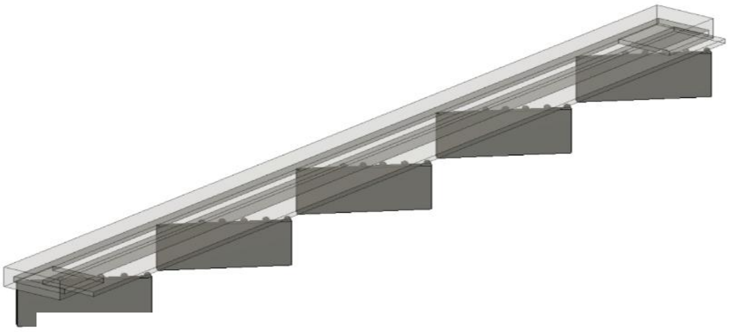
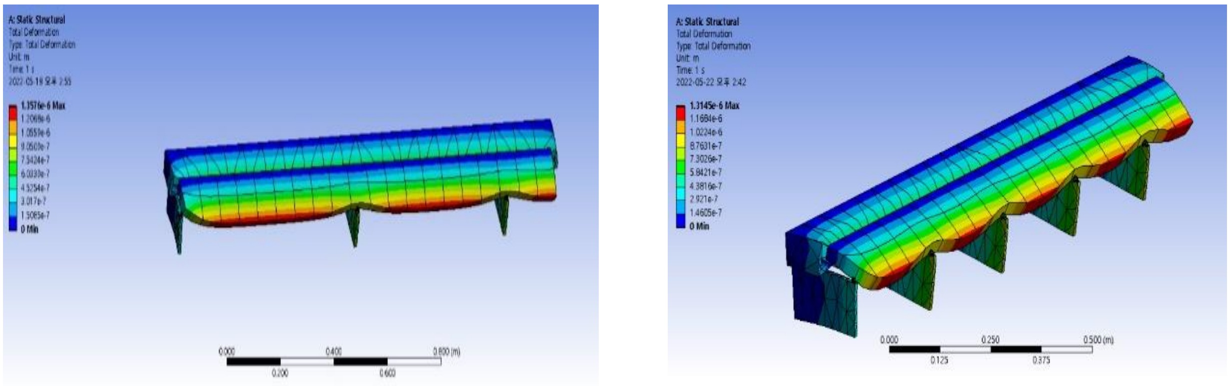


Figure 11: 3D modeling of the safety board interior

After restraining other parts except the number of supports, deformation analysis was performed to find out the deformation amount according to the number of supports when the maximum allowable vertical distribution load of 500 kgf was applied to the safety platform. The number of supports was modeled as 3, 4, and 5, respectively.

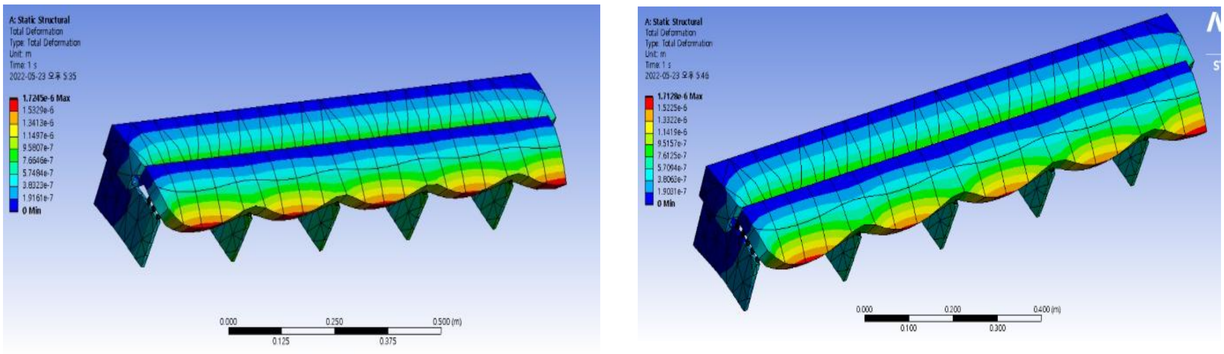


(a) 3 supports (b) 5 supports

Figure 12: Deformation of safety board

Fig. 12 shows the analysis results for cases with 3 and 5 supports, respectively. As a result of the analysis, the maximum deformation when there are 3 supports is 0.001387 mm, and the maximum deformation when there are 5 supports is 0.001314 mm. Although the distributed load applied to the safety board is constant, the maximum deformation at the end of the safety board is found to be 5.5% less when there are 5 supports than when there are three.

An analysis was performed to determine the amount of deformation according to the number of balls when the maximum allowable vertical distribution load of 500 kgf was applied to the safety board. The analysis results for 3 balls and 5 balls are shown in Fig. 13, respectively. The analysis results show that the maximum deformations are 0.001824 mm and 0.001618 mm, respectively. This shows that when there are 5 balls, the maximum deformation is reduced by 12.7% compared to when there are 3 balls.

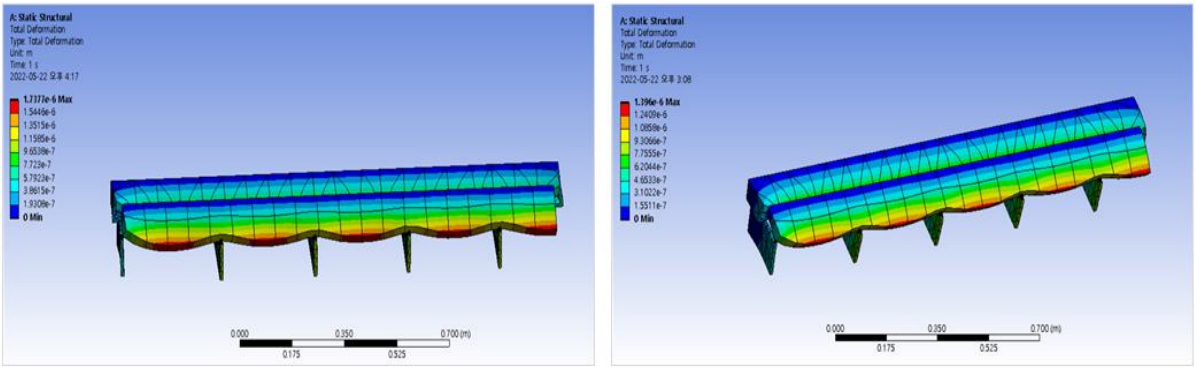


(a) 3 balls (b) 5 balls

Figure 13: Deformation of safety board

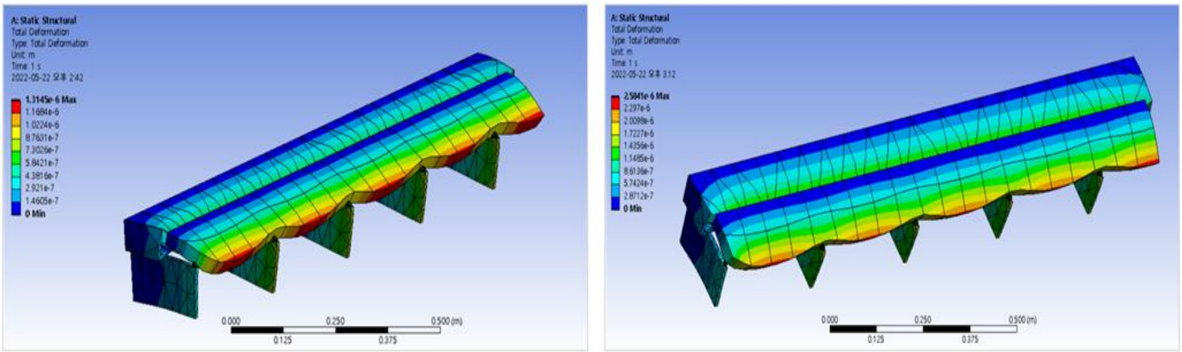
Based on the interpretation results above, the number of supports was selected as the 5 with the smallest maximum deformation, and other parts were restricted. Then, deformation analysis was performed to find out the deformation amount according to the material when the maximum allowable vertical distribution load of 500 kgf was applied to the safety step. At this time, the materials used in the analysis were set to STS304L, STS316L, STS630, and titanium alloy.

Fig. 14 shows the analysis results for materials STS304L and STS360L, and the maximum deformation values were 0.00253 mm and 0.00258 mm, respectively. Also, Fig. 15 shows the analysis results for materials STS630 and titanium alloy, and the maximum deformation values were 0.00131 mm and 0.00261 mm, respectively.



(a) STS304L (b) STS360L

Figure 14: Deformation of safety board according to material



(a) STS630 (b) Titanium alloy

Figure 15: Deformation of safety board according to material

When comparing the maximum deformation values by material, STS630 had the smallest value at 0.00131mm, and titanium alloy had the largest value at 0.00261 mm.

V. DISCUSSION

Based on the final design plan that reflected five supports, material stainless steel 630, and five balls selected considering safety and economy, analysis was performed considering the thickness of the footing as a design variable, and as a result, it was found that the minimum thickness of the footing must be 4.3 mm to be safe.

In this study, a structure was designed to connect the collision protection plate and the load support with a bar to prepare for an unexpected electric train collision. When the electric train and the collision protection plate collide, the collision protection plate folds and the supports fold at the same angle, preventing the collision between the electric train and the step. After the electric train passes, the supports return to the original angle by the spring, and the two-stage step also returns to its original state.

The maximum allowable vertical distributed load of the safety step frame is designed to be 1000 kgf or more, and the maximum allowable vertical distributed load of the movable step is designed to be 500 kgf or more. The basic structural design was calculated assuming that the thickness of the step has at least 2 support points to secure maximum safety. After obtaining the maximum moment value, it was found to be safe when it was 22.7 mm using the section coefficient formula.

Considering the processing error, the thickness of the step is designed to be 23 mm.

The width of the safety step is designed to be 1500 mm for the first stage and 1450 mm for the second stage, considering that the average width of the subway platform is 1300 mm. The length of the safety step is designed to be 100 mm for the first stage and 90 mm for the second stage, considering that the regulation requires that the safety step be installed when the gap between the platform and the train is 10 cm or more and that the maximum width of the platform gap is 28 cm. Considering the allowable load, the height of the support is designed to be 100mm, the length is 190mm, and the thickness is 10mm.

After setting the value derived through theoretical analysis as the basic value, the optimal design was performed by sequentially determining the number of supports, the number of balls, and the size through comparative analysis using ANSYS modeling analysis.

VI. CONCLUSION

In this study, we analyzed the limitations of the existing subway safety board and discussed the problems they cause. These problems mainly occur on platforms due to the vehicle-to-platform gap standards. As an alternative, we suggested a subway safety step that can adjust the length according to the gap for each platform.

As a solution, we designed a subway safety board that considers both economy and safety. The ideas were proposed based on the existing subway safety boards, and the alternatives were compared and analyzed to select the optimal alternative that does not require a power source and can adjust its length according to the gap between the subway and the platform. Next, the design was further optimized by changing different elements of its shape. The proposed model was improved based on the results of a comparative analysis of material type. It was confirmed that the deformation amount was the smallest for the structural steel. However, considering the internal installation conditions such as moisture in subway stations, safety was confirmed by using the stainless-steel 630 model, which is highly corrosion-resistant and economical.

Further improvement was made through a comparative analysis of using different number of supports. It was confirmed that the maximum deformation decreased and the load was more evenly distributed as the number of supports increased. Then, the model was further optimized through a comparative analysis of the number of balls used in the design. It was confirmed that the deformation decreased and the load was more evenly distributed as the number of balls increased.

Finally, it was confirmed that the load was most evenly distributed for the obtained design, and minimal deformation occurred when the number of supports and balls was highest. In addition, the choice of stainless steel 630 as primary material ensured safety while improving the economic efficiency and corrosion resistance. Based on these results, an optimal structure was selected, the safety step design was finalized, and its effects on deformation and stress reduction were confirmed through an ANSYS analysis. Thus, applying the finalized design to subway platforms can yield the aforementioned results.

VII. ACKNOWLEDGEMENTS

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