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131

Research on Envionmental Resistance Performance of Disaster Temporary Housing Modular Houses using Large-Scale Environmental Testing Chamber

Seung-Taek Ahn* · Sang-Tae No**

* First author, Graduate Student, Dept. of Architectural Engineering, Korea National Univ. of Transportation., South Korea (cookie_ahn@a.ut.ac.kr)
** Corresponding author, Professor, Dept. of Architectural Engineering, Korea National Univ. of Transportation., South Korea (stno@ut.ac.kr)

ABSTRACT

Purpose: As climate change escalates, the severity of domestic disasters increases, prompting government support for temporary housing solutions like tents, mats, and modular houses in public spaces. Traditional temporary accommodations like gyms and school playgrounds, while rapid to deploy, suffer from inadequate privacy, sanitation, heating, and cooking facilities. Additionally, prefabricated and container houses face issues like prolonged setup times and poor insulation, heating, and environmental stability. **Method:** This study assesses modular housing as a potential temporary residential solution by evaluating its performance in various environmental conditions. Key metrics include insulation, condensation prevention, and waterproofing. **Result:** The findings indicate that modular houses meet necessary performance standards under diverse environmental stressors, such as rain and strong winds, without leakage. Therefore, modular housing is poised to address the deficiencies of current temporary housing setups, offering improved living conditions for disaster victims. Further research is suggested to optimize the supply, maintenance, and long-term viability of modular housing systems.

KEYWORD

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Climatic Environment
Modular House
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1. Introduction

1.1. Research Background and Purpose

Escalating climate change increases natural disaster damage in South Korea. The Korean government has utilized tents or mats in large indoor spaces, such as village halls, gyms, and school playgrounds, or provided prefabricated, apartment, and container houses for disaster victims. Gyms or school playgrounds can rapidly accommodate many people in response to sudden disasters; however, they often cause inconvenience owing to the outdoor locations or absence of personal living space, sanitation, heating, and cooking facilities. Open spaces also cause such problems as invasion of privacy and exposure to noise [1].

Temporary houses (prefabricated and container houses) involve the inconvenience of moving to residential spaces several times owing to their prolonged setup times, and their low performance (e.g., insulation, heating, and the impacts of external weather conditions) causes other problems [2].

For modular houses, main structures, electric/water equipment, and finishing materials that are produced in advance in factories are assembled at the site. Since 70%–80% of major members and components that constitute housing can be produced in standardized module units, pleasant temporary living spaces can be prepared at a low cost within a short period of time. This study aims to analyze the applicability of modular houses as temporary residential facilities by measuring their insulation and waterproof performance to address problems with conventional temporary residential facilities.

1.2. Research Scope and Methods

The research scope was limited to modular houses constructed and used for residential purposes to examine their applicability as temporary residential facilities. The research methods of this study are as follows.

First, the direction of research is set by analyzing previous studies related to conventional temporary residential facilities.

Second, based on the analysis of previous studies, heat and waterproof experiments are performed, and the results are analyzed.

Third, conclusions and future directions on the applicability of modular houses as disaster temporary housing are presented based on the analysis results.

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2. Theories and Previous Studies

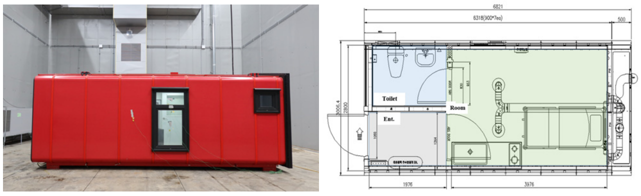
2.1. Status of Temporary Residential Facilities

K. H. Kim et al. conducted a satisfaction survey with the victims of the Pohang Earthquake who stayed in indoor gyms. They raised complaints about the unsanitary conditions caused by the outdoor locations of convenience facilities (e.g., bathrooms, kitchens, and laundry) and the difficulty in protecting privacy owing to the lack of sleeping and personal spaces [1].

S. H. Lee et al. investigated resident satisfaction by conducting a field investigation and a survey of disaster victims who were supported with temporary housing. They found that most disaster victims had evacuation experiences for approximately four months (or more), during which temporary housing was provided after the occurrence of the disaster; moreover, when temporary housing is provided, the first requirement is to improve indoor ventilation, the number of rooms, and the support period. The survey results show that the living area, insulation performance, and safety under external weather conditions (e.g., rain and strong winds) must be improved [2].

Y. R. Seo et al. also conducted a survey with disaster victims on satisfaction with conventional temporary residential facilities. They presented the status of conventional temporary residential facilities based on the survey results, including insufficient sanitation facilities, low comfort caused by high indoor humidity and noise, and inconvenience caused by privacy exposure [3].

This study aims to analyze the applicability of modular houses to address the problems with conventional temporary residential facilities derived from the results of previous studies. Experiments were performed to measure thermal and waterproof performance, which is closely related to residential comfort.



(a) Exterior (b) Floor plan

Fig. 1. Modular house

Table 1. Detailed specifications of modular homes

Building size (W×L×H)		(3.01×6.72×2.60)m		
Internal structure		Entrance, Room. Bathroom, Kitchen		
Insulation structure	Wall. Roof	External insulation (0.118W/m^2·℃),		
	Window	Low-Emissivty Triple glass (0.953W/m^2·℃)		
	Entrance door	Steel fire door (1.391W/m^2·℃)		
Air conditioning	Heating	Heating capacity	6.5kW	COP : 2.99
		Power consumption	2.07kW	
	Cooling	Cooling capacity	4.0kW	COP : 2.36
		Power consumption	1.69kW	

3. Modular House Performance Measurement

3.1. Target Modular House

In this study, a residential modular house that meets the thermal transmittance standards and equipment for buildings by region specified in the Temporary Housing Prefabricated Housing Operation Guidelines [4] was selected as a target (Fig. 1. and Table 1.). It is a unit-type modular house, and the main materials of the outer wall are steel frames, mineral wool, and synthetic resin finishing materials.

3.2. Experimental Facility

The large-scale environmental testing chamber used is a large-scale experimental facility in which various environmental conditions can be set, including temperature, rain, snow, and sunlight. To measure the modular house's environmental

Fig. 2. Large-scale environmental testing chamber

Table 2. Large-scale environmental testing chamber detailed specifications

Environmental conditions	**Environmental scope**
Temperature (℃)	-40~65
Humidity (% R.H.)	10~95
Rain (mm/h)	Max 150
Snow (mm/h)	Max 50
Sunlight (W/m^2)	27.5~1200

resistance performance, experiments were performed by simulating temperature, rain, and strong wind environmental conditions (Fig. 2. and Table 2.).

3.3. Thermal Performance Experiment

In the survey on satisfaction with temporary housing, the problem of poor insulation performance was raised [3]. Accordingly, the thermal performance (insulation and condensation) of the modular house was measured to analyze whether the problem could be improved.

To measure the insulation performance of the modular house, the Building heat Loss Coefficient (BLC) was calculated after setting high-temperature and low-temperature environmental conditions. The environmental conditions of the testing chamber were set to 50℃ for summer considering the maximum temperature and the roof surface temperature caused by sunlight in Korea and −20℃ for winter considering the minimum temperature, roof surface freezing, and snow. Indoor environmental conditions were set based on the seasonal comfort range of ASHRAE Standard 55-2017 [5] (Table 3.).

Table 3. Environmental conditions of insulation performance experiment

	High temperature environment		**Low temperature environment**	
Location	Chamber	Indoor	Chamber	Indoor
Temperature (℃)	50 ± 2	24 ± 2	-20 ± 2	22 ± 2

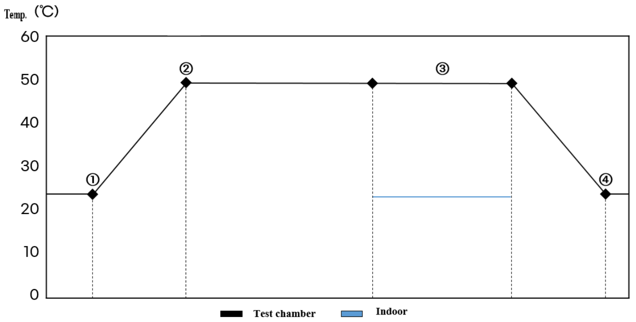


Fig. 3. High temperature environmental conditions profile

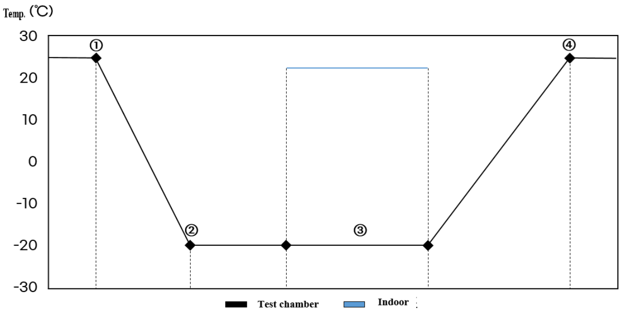


Fig. 4. Low temperature environmental conditions profile

The experimental procedure for high-temperature environmental conditions is shown in Fig. 3. and that for low-temperature environmental conditions in Fig. 4.

[Step-①] Place the target modular house in the testing chamber and set the environmental condition of the chamber to 50℃.
[Step-②] Set the indoor environmental condition to 24℃ and check whether chamber and indoor environmental conditions remain constant.
[Step-③] Measure the data required to obtain BLC.
[Step-④] Calculate BLC after setting chamber and indoor environmental conditions to standard atmospheric conditions.

[Step-①] Place the target modular house in the testing chamber and set the environmental condition of the chamber to -20℃.
[Step-②] After reaching -20℃, check whether the set environmental condition remains constant.
[Step-③] Maintain the indoor environmental condition at 22℃ by operating indoor air conditioning.
[Step-④] Measure data and calculate BLC when chamber and indoor environmental conditions remain constant.

To analyze the modular house's thermal performance, the theoretical BLC value that used the thermal transmittance of each part (BLC_{KAT}) was compared with the values calculated by measuring the electrical energy of cooling/heating devices and the air-conditioning flow rate (BLC_{COP}, BLC_{mcdt}).

First, BLC for each part (BLC_n) of the building (ceiling, floor, walls, windows, and doors) was calculated by multiplying its area (A) and thermal transmittance (U) (Eq. 1)

$$BLC_n = U \times A \qquad \text{(Eq. 1)}$$

The theoretical BLC value (BLC_{KAT}) was obtained by adding the calculated BLC value of each part (BLC_n) (Eq. 2).

$$BLC_{KAT} = BLC_1 + BLC_2 + \cdots + BLC_5 \qquad \text{(Eq. 2)}$$

($BLC_{1\sim5}$: *In order of ceiling, floor, walls, windows, and doors)*

The cooling/heating load (Q) was calculated by multiplying the electrical energy (W) of cooling/heating devices measured at [step-③] by COP (Eq. 3), and the BLC measurement (BLC_{COP}) was calculated by dividing it by the indoor and outdoor

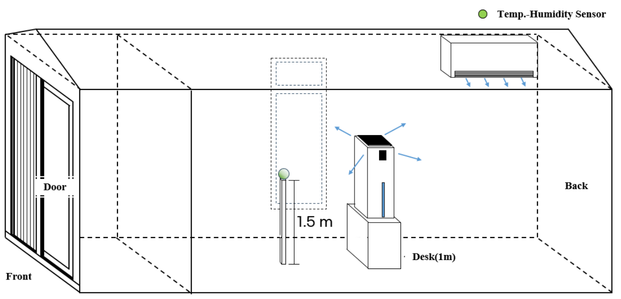


Fig. 5. Deployment of condensation performance experimental equipment

temperature difference ($\triangle T$) (Eq. 4).

$$Q = COP \times W \quad \text{(Eq. 3)}$$

$$BLC_{COP} = \frac{Q}{\triangle T} \quad \text{(Eq. 4)}$$

The mass flow rate ($\dot{m}$) was calculated using the discharge temperature, intake temperature, and wind speed of cooling/heating devices measured at [step-③]. The total heat loss/heat acquisition (Q) was calculated using the mass flow rate, specific heat of the air (C_p), and difference between the discharge and intake temperatures ($\triangle T_{i-o}$), and the BLC measurement in consideration of the air-conditioning flow rate (BLC_{mcdt}) was calculated by dividing it by the indoor and outdoor temperature difference (Eq. 7 and Eq. 8).

$$Q = \dot{m} \times C_p \times \triangle T_{i-o} \quad \text{(Eq. 7)}$$

$$BLC_{mcdt} = \frac{Q}{\triangle T} \quad \text{(Eq. 8)}$$

Equipment was arranged to measure the modular house's condensation performance, as shown in Fig. 5. Chamber and indoor environmental conditions were set based on KS F 2295 [6] and design standards for condensation prevention in multi-family housing [7] (Table 4).

The experiment was conducted in stages, as shown in Fig. 6.

[Step-①] Set the chamber environmental condition to a temperature of −20℃ and indoor environmental conditions to a temperature of 20℃ and a relative humidity of 40%.

[Step-②] Check whether chamber and indoor environmental conditions remain constant when the chamber temperature reaches −20℃ (stabilization).

Table 4. Condensation performance experiment environmental conditions

	Chamber	Indoor
Temperature (℃)	-20 ± 2	20 ± 2
Humidity (% R.H.)	-	40 ~ 60

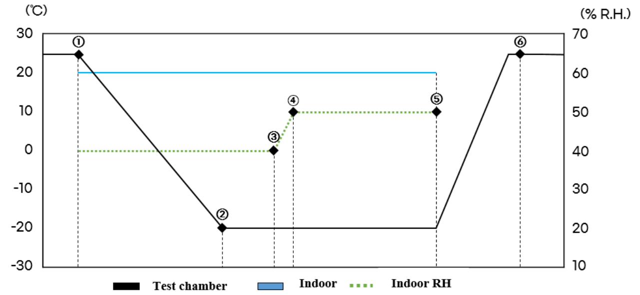


Fig. 6. Condensation performance experimental profile

[Step-③] Increase the indoor relative humidity from 40% to 50%.

[Step-④] Maintain the environmental conditions for a certain period of time when the indoor relative humidity reaches 50%.

[Step-⑤] Visually inspect the occurrence of indoor surface condensation.

[Step-⑥] Calculate results after adjusting chamber and indoor environmental conditions to standard atmospheric conditions.

The dew point temperature (T_{dc}) was calculated through the measured indoor temperature (T) and humidity (RH) (Eq. 9). When the measured surface temperature of each indoor part (ceiling, floor, walls, windows, and doors) was high, no condensation occurred.

$$T_{dc} = \frac{c \times [\ln(\frac{RH}{100}) + \frac{b \times T}{c+T}]}{[b - \ln(\frac{RH}{100}) + \frac{b \times T}{c+T}]} \quad \text{(Eq. 9)[8]}$$

b, c : a constant(b = 17.62, c = 243.12)

3.4. Waterproof Performance Experiment

To measure the waterproof performance of the modular house, the house and equipment were arranged as shown in Fig. 7.

For storm environment simulation conditions, the maximum precipitation per hour and maximum wind speed in the summer over the last 10 years were investigated. Precipitation was found to range from 90 to 110mm/h, and wind speed ranged from 17 to 30m/s. Environmental conditions were set considering weather

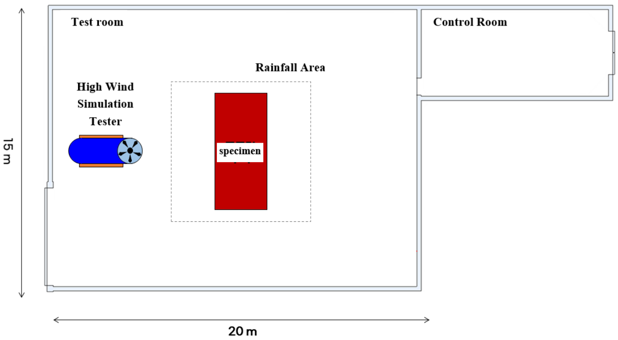


Fig. 7. Layout of waterproof performance test equipment

Table 5. Waterproof performance test environmental conditions

	Chamber
Temperature (℃)	Standard atmosphere
Humidity (% R.H.)	
Rain (mm/h)	100 ± 6
Wind (m/s)	18

Fig. 8. Waterproof performance experimental procedure (Front, right, left, back in that order)

information and the performance of equipment (Table 5.).

[Step-①] Place a wind generator and the modular house in the chamber and visually check for abnormalities.
[Step-②] Expose the modular house for a certain period of time by simulating the storm environment.
[Step-③] Stop environmental simulation and check for indoor leakage.
[Step-④] Repeat [step-②] and [step-③] for every side of the modular house and record the results.

4. Modular House Performance Evaluation

4.1. Thermal Performance Evaluation

To analyze the modular house's thermal performance, the theoretical BLC value (BLC_{KAT}) and measurements (BLC_{COP}, BLC_{mcdt}) calculated using each equation were compared and analyzed (Table 6.).

Table 6. Experimental results of insulation performance

	High temperature environment	**Low temperature environment**
Theoretical value (BLC_{KAT})	12.05	
COP measures (BLC_{COP})	27.26	-
Air conditioning flow rate measures (BLC_{mcdt})	21.09	20.80

Fig. 9. Checking for condesation in a modular house (Order of windows, doors, and walls)

The results in Table 6. show that the theoretical value (BLC_{KAT}) was approximately 56% lower than the measurements (BLC_{mcdt}, BLC_{COP}), and the measurements (BLC_{mcdt} and BLC_{COP}) were similar with a relative error of 23%.

Substantial differences existed between the theoretical value and measurements because the theoretical value (BLC_{KAT}) represents ideal performance as it is the value calculated by considering only the thermal transmittance of each part of the modular house, while the measurements (BLC_{mcdt}, BLC_{COP}) include the heat loss caused by infiltration through envelop angle, joint, window, and door gaps. Since considerable differences were observed between the theoretical value and measurements, preparing methods and standards for evaluating the performance

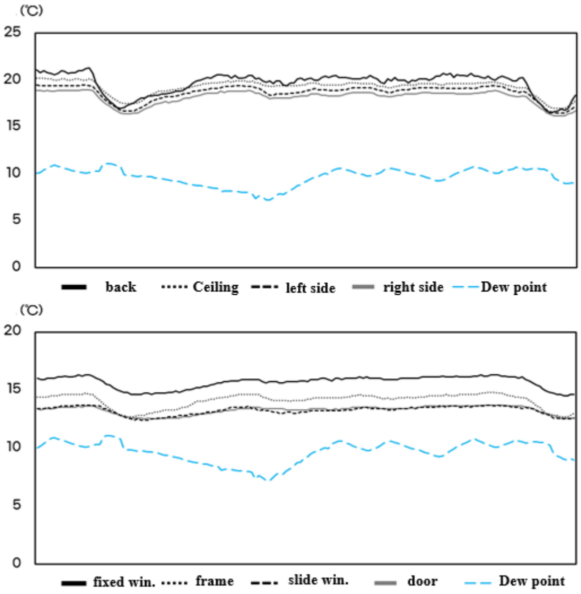


Fig. 10. Comparison graph of dew point temperature and each surface temperature

of temporary housing modular houses through experiments with various samples of modular houses will be necessary in the future.

4.2. Condensation Performance Evaluation

When indoor walls and windows were visually inspected, no condensation was found, as shown in Fig. 9. A comparison between the calculated dew point temperature and each surface temperature (Fig. 10.) revealed that all surface temperatures were higher than the dew point temperature, which indicates that no condensation occurred indoors, and wintertime insulation performance was secured.

4.3. Waterproof Performance Evaluation

Indoor leakage was visually inspected after stopping environmental conditions at [step-③]. The parts inspected were the angles and corners of each wall as well as window and door gaps, which are considered vulnerable to leakage.

No leakage was found in the parts as shown in Fig. 11.-13. If the modular house is used as a temporary residential facility, no leakage problem will arise even in strong wind and rainfall environments during summertime.

Fig. 11. Checking for window waterproofing performance

Fig. 12. Checking for corner and angle waterproofing performance

Fig. 13. Checking for door waterproofing performance

5. Conclusion

This study analyzed the applicability of modular housing as temporary residential facilities by evaluating its performance to address problems with conventional temporary residential facilities for disaster victims, and the results can be summarized as follows.

In the event of a disaster, disaster victims stay in large-scale facilities (e.g., playgrounds and gyms) or independent temporary houses (e.g., prefabricated and container houses). For large-scale facilities, the inconvenience of living and long period of relocation to temporary housing were raised as problems. In the case of temporary houses, poor insulation performance, rainwater leakage, and the impact of wind were raised as problems. To address these problems, analyzing the applicability of modular houses as temporary residential facilities was set as the purpose of this study.

Based on the problems raised from conventional temporary residential facilities, experiments were performed with a focus on thermal performance (insulation and condensation) and waterproof performance, and performance was measured under the environmental conditions set based on domestic standards.

When insulation performance was measured under high-temperature and low-temperature environmental conditions, the Building heat Loss Coefficient (BLC) measurement (BLC_{KAT}) that considered the thermal transmittance of each part was almost similar to the heat acquisition and heat loss caused by angle, window, and door gaps, which indicates that insulation performance for vulnerable parts was secured.

When the indoor humidification environment was maintained under low-temperature environmental conditions, no condensation occurred on all surfaces (walls, windows, and doors) and the surface temperature on each side was higher than the dew point temperature, indicating that insulation performance for preventing condensation was secured.

In the waterproof performance experiment results, no leakage occurred at indoor angles and gaps even under harsh environmental conditions (100mm/h rainfall per hour and a wind speed of 18m/s), confirming sufficient waterproof performance.

Modular housing in this study is expected to improve problems with conventional temporary residential facilities and provide disaster victims with more pleasant residential environments; however, this study has limited samples as it targeted a ready-made product. In the future, evaluating various modular houses as temporary residential facilities will be necessary. Further research will be required on systematic planning for the dissemination of modular houses, comparisons with overseas cases and standards, related systems, and maintenance plans due to long-term residence.

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