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Wind Resistance Performance Evaluation of Cable-Type Curtain Wall System on Reinforced Concrete High-Rise Buildings

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Abstract

In this research, a cable-type wall system that could replace the conventional aluminum curtain wall system for reinforced concrete high-rise buildings is proposed. The cable-type wall system is a newly developed system, which could be used as an existing exterior skin system, and can effectively support the wind load acting on the exterior of the high-rise buildings by the pre-induced initial tension force to the cable supporting the glass. The main advantages of the cable-type wall system are that the expense of construction could be reduced due to the simplicity of the construction. The experiment of structural analysis and air/water tightness was performed to evaluate its feasibility of industrialization. The structural performance of the cable-type wall system was evaluated through the structural analysis and the full-scale experiment to predict the initial pre-tension force and the design load displacement of the vertical one-way cable-type wall system that can be used for a typical floor of the high-rise building. The initial pre-tension force and structural behavior of the cable were analyzed by using the structural design program MIDAS-Gen. The maximum deformation value in the structural test was found to satisfy the AAMA condition, which is equal to the size of the facade skin system. The air/water tightness test was conducted to verify the performance. Test results show that the cable-type wall system satisfies the air/water tightness performance standards ASTM E283, E331 and AAMA 501.1-05 which are the most basic standards that the facade system must provide. As a result of this study, it is expected that the proposed cable-type wall system could be used for facade system, not only the structural performance but also air/water tightness performance are secured.

Keywords: curtain wall, wind resistance, initial pre-tension, cable-type, facade system, structural performance, air/water tightness performance

1 Introduction

1.1 Research Background

Cable structures have been commonly used as structural systems in bridges such as suspension bridges and cable-stayed bridges to control the deflection of long-span structures, and recently they are used in building claddings. Cable structures, which are used for exterior materials of reinforced concrete structures, act on strong positive tension on cables instead of mullion and transom, and secure openness and ease of construction (Park 2002). A typical example is the cable network cladding system where the fixed hardware is installed at the edge points connected vertically and horizontally to fix square or rectangular glass in point shape (Park et al. 2014). This structure is similar to tennis rackets and the external force from the tennis ball causes deformation on the racket frame and tennis strings, which absorbs the energy and back again by the reaction force (Park 2018).

However, it is difficult to find a case in Korea as well as abroad that cable external systems are applied to the standard layer curtain wall of high-rise buildings, and is only applied to lobbies and large spaces of buildings (Park 2017). The reason why cable network systems are not

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being used as exterior materials for high rise buildings is the increased cost of establishing a fixed system of steel members supporting the cable connected vertically and horizontally (Georg et al. 2012). Therefore, to address these problems, this research suggests a cable system that is easy to achieve and build on behalf of aluminum or steel support members that are used as exterior materials for existing reinforced concrete buildings.

1.2 Research Objectives

Cable wall systems support glass by connecting cables in one direction only (Schlaich et al. 2005) offers the advantages of reducing the volume of frames than conventional aluminum enclosures, however the structural analysis of cable behavior is difficult and the construction method is not generally used (Feng et al. 1996). Also, due to the characteristics of the cable performing nonlinear behavior, it is difficult to predict initial tension and select members, and the design of an anchorage zone by strong tension is essential (Choi et al. 2018).

To make the cable system universally available in the curtain wall market, it is easy to predict the amount of variation of cables through the selection of point by point of design load and the accurate prediction of initial tension (Shi et al. 2010). Also, applying to the reference story of high-rise reinforced concrete structures requires a simple system that can complement the complex process of traditional aluminum curtain wall methods as shown in Fig. 1 (Choi et al. 2018). Therefore, to solve these problems, the initial tension and design of cables in vertical, one-way cable-type curtain wall system that can be applied repeatedly to the reference story of a high-rise reinforced concrete structure.

2 Experimental Plan

2.1 Structural Analysis Plan

In this study, the design wind pressure was calculated for the busiest areas, Seoul and Busan in Korea, based on the basic wind speed values for each region presented in the criteria of Korea Building Code (KBC) (2016) 0305.5.2. Design wind pressure Pc for external cladding over 20 m height was calculated by Eq. (1) for static pressure and Eq. (2) for negative pressure in (KBC 2016 0305.4.2, 4.3) as shown in Tables 1, 2.

$$P_c = k_z q_H \left(GC_{pe} - GC_{pi}\right)\left(N/m^2\right) - (\text{KBC 2016 0305.4.2}). \tag{1}$$

$$P_c = q_H \left(GC_{pe} - GC_{pi}\right)\left(N/m^2\right) - (\text{KBC 2016 0305.4.3}). \tag{2}$$

where P_c is a design wind pressure and GC_{pe} is a peak pressure factor for external design.

The criteria for calculating the reference load were set for the Busan area due to the higher design load. According to the Korean Building Code 0305.5.2., the design wind pressure of the exterior surface of approximately

Table 1 Comparison of design wind pressure between Seoul and Busan, (a) Seoul (importance factor 1.0/height of a building 199 m/height of a floor 4.5 m).

Span (m)	Exposure			
	A		B	
1	Typical (+)	1.69 kPa	Typical (+)	2.07 kPa
	Typical (−)	− 1.46 kPa	Typical (−)	− 1.74 kPa
	Edge (−)	− 2.75 kPa	Edge (−)	− 3.26 kPa

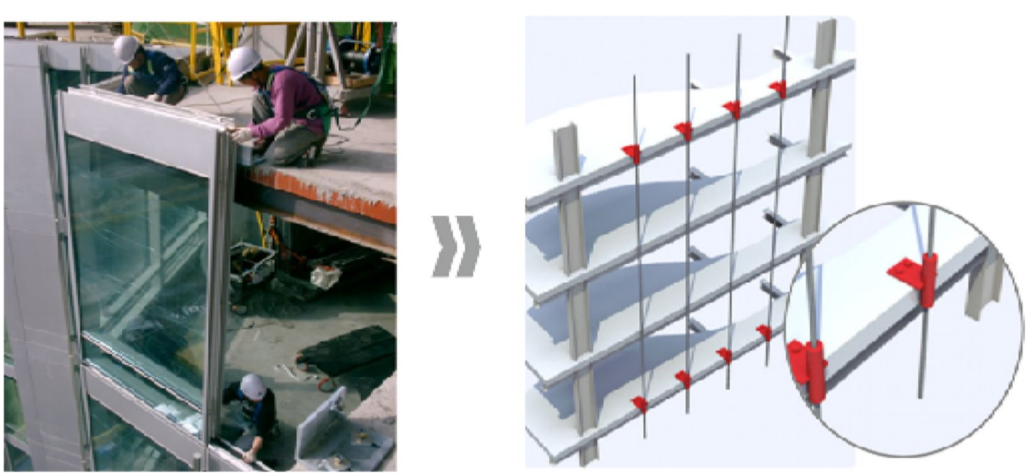

Fig. 1 Comparison of alum. C/wall system and cable C/wall system.

Table 2 Comparison of design wind pressure between Seoul and Busan, (b) Busan (importance factor 1.0/height of a building 199 m/height of a floor 4.5 m).

Span (m)	Exposure			
	C		D	
1	Typical (+)	4.41 kPa	Typical (+)	5.06 kPa
	Typical (−)	−3.70 kPa	Typical (−)	−4.15 kPa
	Edge (−)	−6.95 kPa	Edge (−)	−7.80 kPa

200 m skyscraper is a static pressure of 5.06 kPa, negative pressure 1 (typical) of −4.15 kPa and negative pressure 2 (edge) of −7.80 kPa, corresponding to the surface roughness category D of the Busan area with a basic wind speed of 38 m/s. Since the design wind pressures may differ slightly depending on the effective projected area and location of the cladding, the reference wind pressure was set at 5.0 kPa, similar to the external static pressure of the design load above.

Through the case studies of a typical high-rise office building, the design conditions were determined by applying a layer height of 4.5 m, module 1.0 m to 1.25 m.

The structural analysis model implements a 20 mm diameter cable at 2 span with 4.5 m length and the curtain wall module for loading design wind pressures of 5.0 kPa is 1.0 m and 1.25 m. To check the deformations of cables according to the changes in tension of cables and the change in initial tension, the initial tensions were 20%, 25%, 30%, and 40% of the maximum tensile strength of cables (refer to Figs. 2 and 3).

The loading position is designed to accommodate the lower spandrel part 1000 mm, view part 2900 mm, and upper spandrel part 600 mm from the floor level according to the typical window design conditions.

MIDAS GEN Program (MIDAS 2016) was used for the structural analysis. The nonlinear analysis ensures that the displacement of the cable at each point is within the allowable limit defined in American Architectural Manufacturers Association (AAMA) (2002).

2.2 Test Specimen Design

A cable tensile force device was constructed using a steel tube pipe to measure the tensile strength of the cable supporting the glass as shown in Fig. 4. Two spans in two stories with story height of 4.5 m specimen was tested, which is in equivalent condition as analytical model. Breaking load (P_{break}) of the 20 mm diameter spiral cable used in the test was 324 kN. Material properties of cable is shown in Table 3.

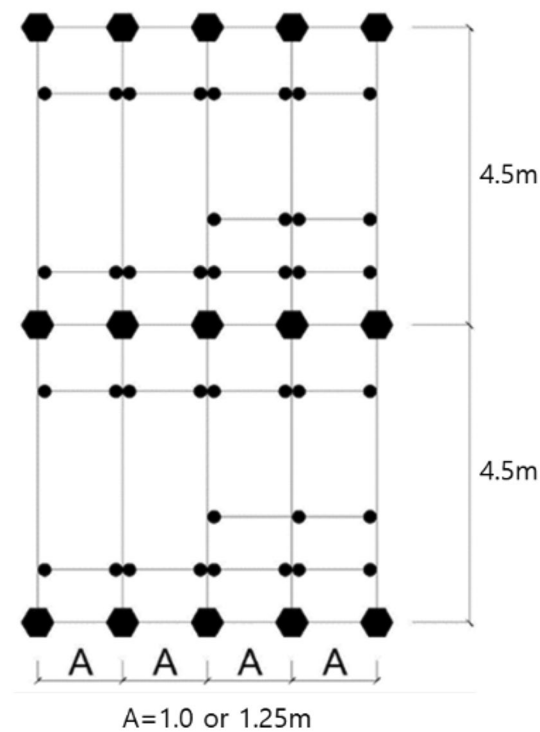

Fig. 2 Structural analysis model.

The specimen was tested horizontally. A vertical force was applied to the specimen at the positions of 1000 mm and 2900 mm from the bottom where the transoms are located as shown in Fig. 5. To estimate the proper initial tension on the same cable, the positive tension of the cable changed to 20%, 25%, 30%, and 40% of the cable breaking tensile strength to check displacement and stress.

Since the tension of cables varies greatly according to the temperature change after the positive tension is applied, the cables shall be tested at the room temperature so that no change in tension occurs after the positive tension was applied. It was required to reconfirm the change of tension through the force measuring device after the tensile force is applied to load the tensile force accurately.

2.3 Air/Water Tightness Mockup Test

The purpose of this study is to propose a cable wall system as a complete external cladding, which requires verification of the basic air/water tightness performance of the cladding. Therefore, three spans in two stories, which was the basic condition of the mock-up of the cladding, were implemented in the same way as the actual construction conditions including fixed glass, opened glass,

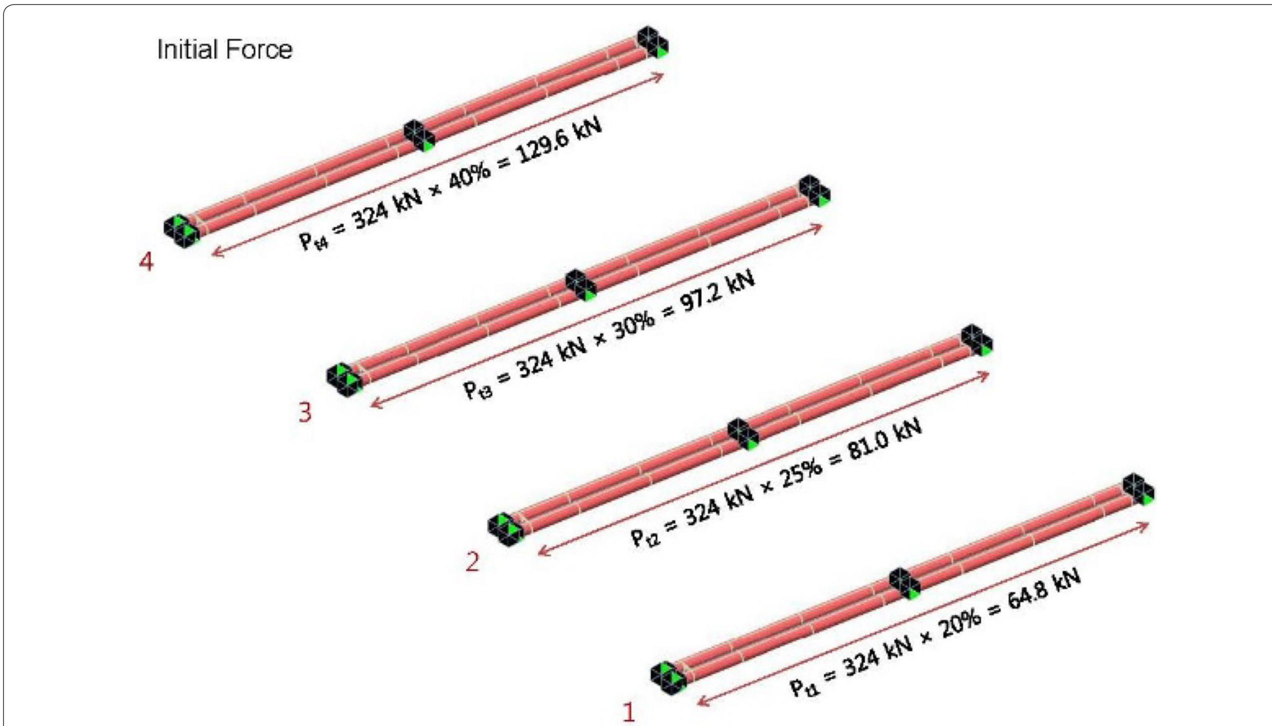

Fig. 3 Structural analysis model (initial force 20%, 25%, 30%, 40%).

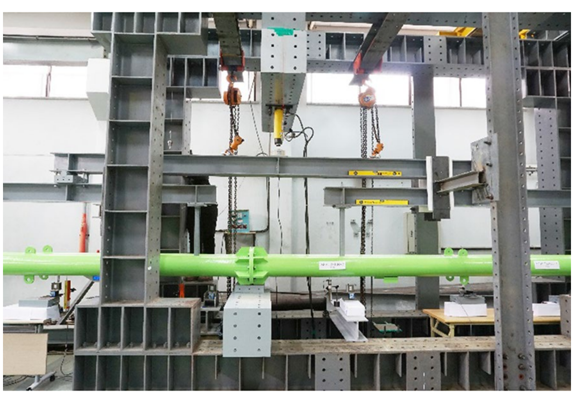

Fig. 4 Test of cable wall system.

Table 3 Material properties of cable.

Diameter (mm)	Modulus of elasticity (GPA)	Area (mm^2)	Breaking load (kN)	Ultimate strength (MPa)
20	160	240	324	1470

and even structures for verification according to the American Society for Testing Materials (ASTM) E283-04 (2002) and ASTM E331-00 (2002).

The air tightness performance test was conducted to maintain a test standard pressure of 74.5 kN/m^2 on the specimen for the test conditions of ASTM-E283, and then air flow from the specimen was measured as shown in Figs. 6 and 7.

The water tightness test was conducted on the specimen to check for water leaks of 204 L/m^2 spraying for 15 min while maintaining a static pressure 720 Pa specified in the specification ASTM-E331 to comply with the experimental conditions as shown in Figs. 8 and 9.

3 Structural Analysis and Experimental Results

3.1 Structural Analysis Results

Structural analysis is shown in Table 4 by performing a geometric nonlinear analysis using the MIDAS GEN program. In the case of Span 1.0 m for 5.0 kPa, the international allowable deflection L/50 (AAMA 1996) was satisfied for all four positive initial tensions which were 20%, 25%, 30%, and 40% of P_{break}. Also, the results demonstrates that the allowable deflection is satisfied for span 1.25 m with 5.0 kPa loads as shown in Table 5.

The member stress of the cable was determined based on the cable design code KASS (2009), and the allowable load of the cable is equal to the breaking load divided by the safety factor 3 and the short-term stress coefficient multiplied by 1.33 for the wind load.

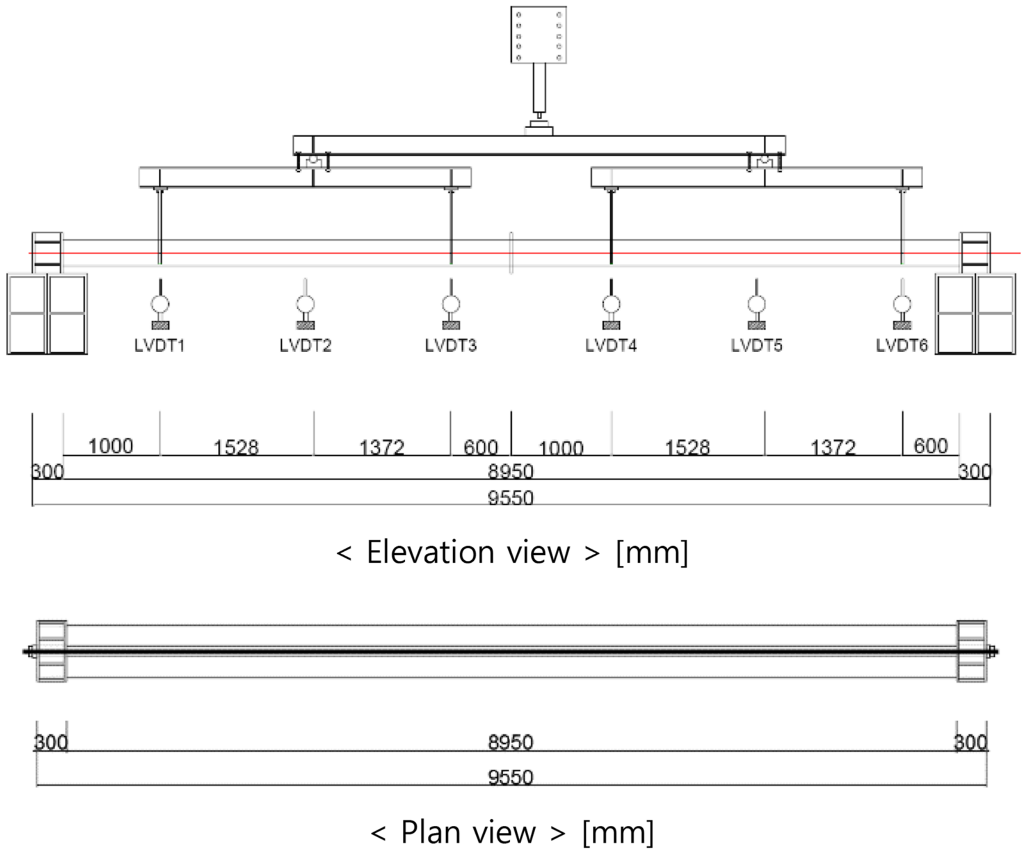

Fig. 5 Test setup and measurement.

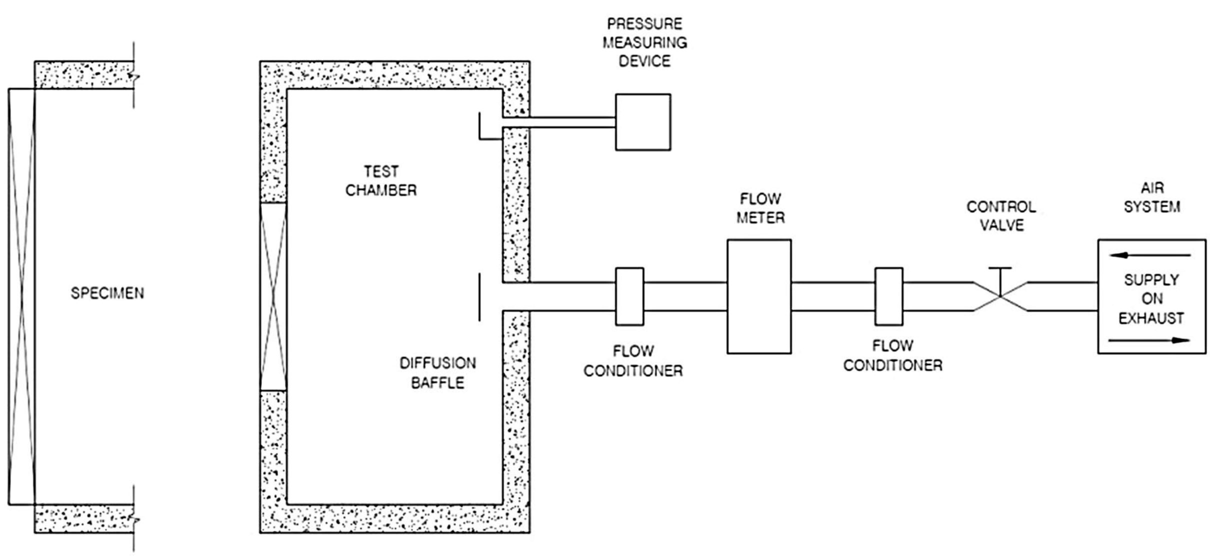

Fig. 6 General arrangement of the air leakage test apparatus.

Fig. 7 Vent operation and air tightness performance test.

The results of allowable tensile force calculated from the results of the structural analysis are shown in Table 6. Cable member stresses were within acceptable limits at a force ratio of about 90% to the tensile force of up to 30%. At 40% of the tensile strength, about 7% of the allowable stress was exceeded for span 1.0 m specimen, and approximately 14% of the allowable stress for span 1.25 m specimen. Typically, the cable positive tension should not exceed the allowable stress (breaking force/3) on the long-term load, which is consistent with the test results. However, the allowable load for short-term loads is about 44% of the breaking load, which is somewhat beyond stress at 40% full tension, but with margin up to the breaking load, further studies are required for economic design under the conditions of the applied load.

3.2 Structural Test Results

In the experiment, the cables were subjected to tension in the range of 20%, 25%, 30%, and 40%. In the same condition, the cables were tested sequentially, and they were repeatedly applied under the same conditions. For the design load, the results were verified by applying the load to 1.0 m specimen and the final result was confirmed after the additional load applied to 1.25 m specimen.

For the span 1.0 m for 5.0 kPa, all four initial tensions (20%, 25%, 30%, and 40%) were found to satisfy the international acceptable deflection L/50 as shown in Table 7. In addition, span 1.25 m for 5.0 kPa loads met the allowable deflection L/50 as shown in Table 8.

As shown in Table 9, cable tension showed similar results as the structural analysis results. Up to 30% of the positive tension, the result was within the allowable stress range, however at 40% of the positive tension, stress on width of 1.0 m and 1.25 m exceeded 6.1% and 11.9% of allowable stress range, accordingly. As initial tension increases, actual tension increased and displacement decreased. Comparison of the results of the experiment and the structural analysis are shown in Fig. 10.

In Fig. 11, the change in displacement between the experiment and the structural analysis results showed 90% and 99% match at the initial tensile force 30% and 40%, accordingly.

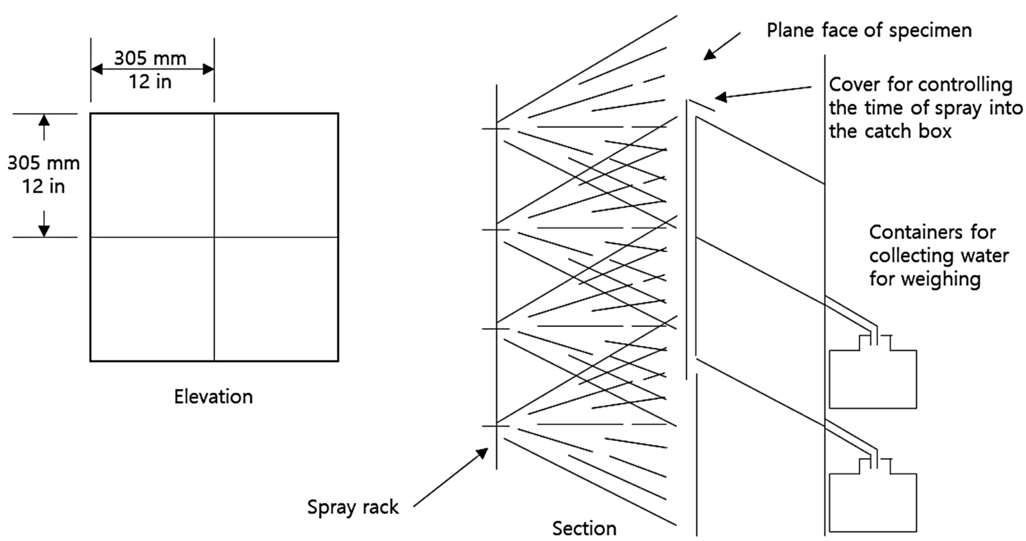

Fig. 8 Catch box for calibrating water-spray system.

Fig. 9 Air/water tightness performance test.

3.3 Results of Air/Water Tightness Mock-up Experiments

For considering the various ambient conditions, air/water tightness tests according to ASTM were conducted. The results of the experiments in accordance with ASTM E283 air tightness performance test are shown in Table 10. The experiment measured the leakage by applying a test standard pressure of 75 Pa and compared it to the allowable values of 0.06 CFM/ft^2 (fixed area) and 0.25 CFM/ft (opened area).

The total size of the curtain wall is 4.18 m by 9.045 m, so it is 37.81 m^2 (406.95 ft^2) and the ventilation perimeter for window is $2 \times [2\ (1.03 + 0.53)]$ m, which is 6.24 m (20.47 ft). The volume of air (Q_{st}) is calculated as 2.28 CFM and 1.32 CFM as shown in Table 10. Total leakages of air per unit under fixed and opened conditions were 0.006 CFM/ft^2 and 0.064 CFM/ft, respectively. These values satisfies the allowable limit of 0.064 CFM/ft^2 and 0.25 CFM/ft, respectively.

The water tightness performance test was conducted under the static and dynamic pressure. Experimental conditions under static pressure as per ASTM E331-00 were,

① Test pressure: +73.2 kgf/m^2 (+720 Pa, 15.0 psi)/ AAMA 501-15 recommendation.
② Amount of spray water: 204 L/m^2 h,
③ Duration: 15 min,
④ Tolerance: no uncontrolled water leakage.

Table 4 W = 1.0 m structural analysis result.

Diameter (20 mm)	P_{break} (kN)	Span = 1.00 m			
		$0.20P_{break}$	$0.25P_{break}$	$0.30P_{break}$	$0.40P_{break}$
$P_{initial}$ (kN)	324	64.8	81.0	97.2	129.6
Δ_{act} (mm)		72.3	66.9	61.9	52.9
Δ_{allow} (mm)		90 (= L/50)			
$\Delta_{act}/\Delta_{allow}$		80.3	74.4	68.8	58.8
P_{act} (kN)		112.5	121.4	131.3	153.2
P_{act}/P_{break}		34.7%	37.5%	40.5%	47.3%

$P_{initial}$: initial force.
P_{break}: breaking force.
Δ_{act}: actual deflection.
Δ_{allow}: allowable deflection.
P_{act}: actual tensile force.

Table 5 W = 1.25 m structural analysis result.

Diameter (20 mm)	P_{break} (kN)	Span = 1.25 m			
		$0.20P_{break}$	$0.25P_{break}$	$0.30P_{break}$	$0.40P_{break}$
$P_{initial}$ (kN)	324	64.8	81.0	97.2	129.6
Δ_{act} (mm)		81.1	76.0	71.1	62.1
Δ_{allow} (mm)		90 (= L/50)			
$\Delta_{act}/\Delta_{allow}$		90.2	84.5	79.0	69.0
P_{act} (kN)		125.2	133.6	142.8	163.2
P_{act}/P_{break}		38.6%	41.2%	44.1%	50.4%

Table 6 Force ratio of the cable.

W (m)	$P_{initial}$	P_{act} (kN)	P_{break} (kN)	P_{allow} (kN)	Force ratio	Remarks
1.0	$0.20P_{break}$	112.5	324	143.64	0.783	O.K
	$0.25P_{break}$	121.4			0.845	O.K
	$0.30P_{break}$	131.3			0.914	O.K
	$0.40P_{break}$	153.2			1.067	N.G
1.25	$0.20P_{break}$	125.2	324	143.64	0.872	O.K
	$0.25P_{break}$	133.6			0.930	O.K
	$0.30P_{break}$	142.8			0.994	O.K
	$0.40P_{break}$	163.2			1.136	N.G

P_{allow}: allowable tensile force = $1.33P_{break}/3$ (KASS 2009).

Table 7 W = 1.0 m Test result.

Diameter (20 mm)	P_{break} (kN)	Span = 1.00 m			
		$0.20P_{break}$	$0.25P_{break}$	$0.30P_{break}$	$0.40P_{break}$
$P_{initial}$ (kN)	324	64.8	81.0	97.2	129.6
Δ_{act} (mm)		64.3	59.5	55.4	52.2
Δ_{allow} (mm)		90 (= L/50)			
$\Delta_{act}/\Delta_{allow}$		71.5	66.1	61.6	58.0
P_{act} (kN)		110.8	119.2	127.5	152.5
P_{act}/P_{break}		34.2%	36.8%	39.3%	47.1%

Table 8 W = 1.25 m test result.

Diameter (20 mm)	P_{break} (kN)	Span = 1.25 m			
		$0.20P_{break}$	$0.25P_{break}$	$0.30P_{break}$	$0.40P_{break}$
$P_{initial}$ (kN)	324	64.8	81.0	97.2	129.6
Δ_{act} (mm)		74.4	69.1	65.2	61.9
Δ_{allow} (mm)		90 (= L/50)			
$\Delta_{act}/\Delta_{allow}$		82.7	76.8	72.5	68.8
P_{act} (kN)		120.9	129.8	137.7	160.8
P_{act}/P_{break}		37.3%	40.1%	42.5%	49.6%

Table 9 Force ratio of the cable.

W (m)	$P_{initial}$	P_{act} (kN)	P_{break} (kN)	P_{allow} (kN)	Force ratio	Remarks
1.0	$0.20P_{break}$	110.8	324	143.6	0.771	O.K
	$0.25P_{break}$	119.2			0.830	O.K
	$0.30P_{break}$	127.5			0.887	O.K
	$0.40P_{break}$	152.5			1.061	N.G
1.25	$0.20P_{break}$	120.9	324	143.6	0.842	O.K
	$0.25P_{break}$	129.8			0.904	O.K
	$0.30P_{break}$	137.7			0.959	O.K
	$0.40P_{break}$	160.8			1.119	N.G

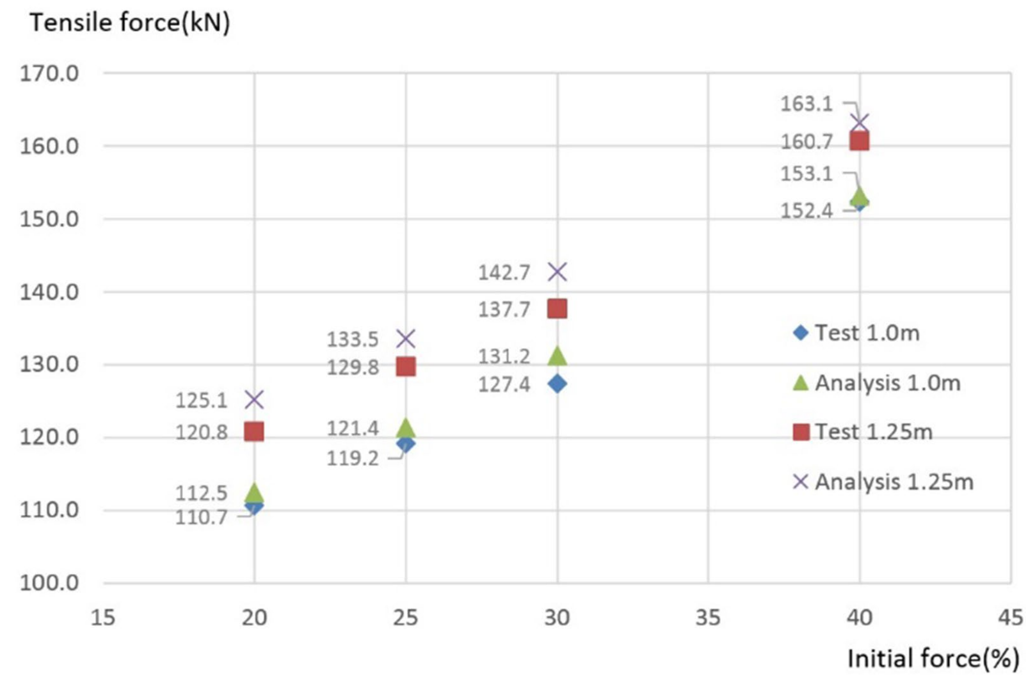

Fig. 10 Comparison of test and analysis for tensile force.

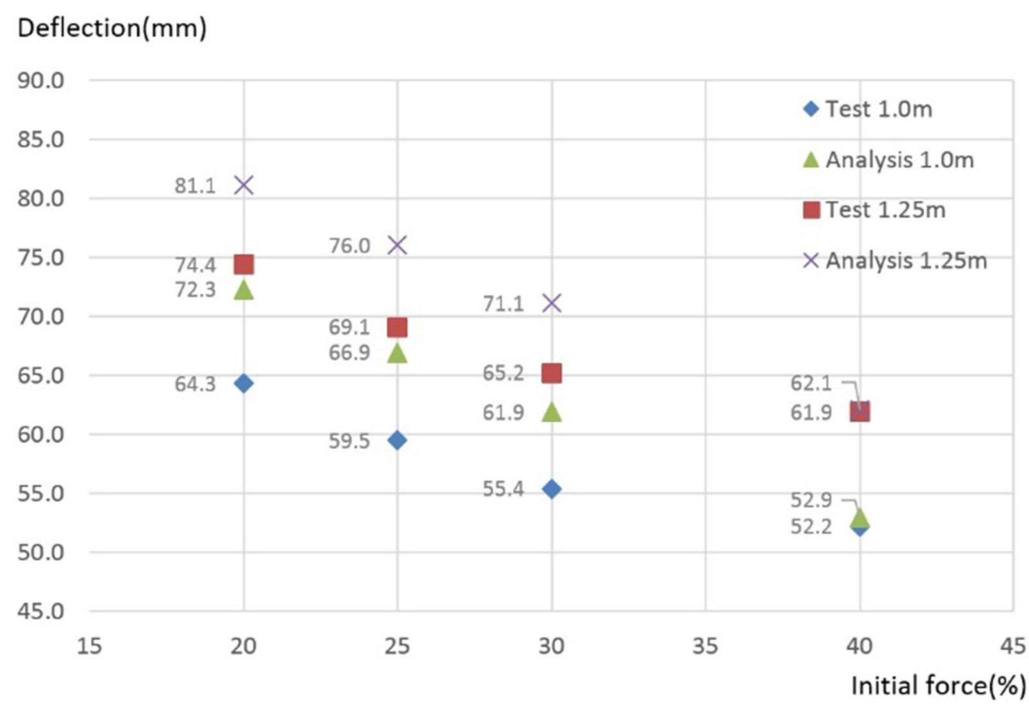

Fig. 11 Comparison of test and analysis for deflection.

Experiments under dynamic pressure was conducted in accordance with AAMA 501.1-05 using the aircraft engine to spray water while blowing the air. These conditions were,

① Test pressure: wind speed equal to static pressure $+73.2\ \text{kgf/m}^2$ could be calculated as $q_0 = \frac{1}{16}V_0$, q_0: basic velocity pressure (kgf/m^2), V_0: wind speed (m/s), $\therefore V_0 = \sqrt{q_0 \times 16} = \sqrt{73.2 \times 16} = 34.05\ \text{m/s}$,

Table 10 Conversion of air flow rate during air tightness test.

Conversion of air flow under standard test conditions from measured air leakage								
Measured air flow				**Standard test conditions**			**W**	**Air flow under standard test conditions (CFM)**
Location	**Total (Q_t)**	**Extraneous (Q_e)**	**Net specimen (Q_s)**	**Pressure**	**Temperature**	**Air density (W_s)**		
Fixed area	4.28	2.0	2.28	1013 (hpa)	20.8 (°C)	1.202 (kg/m^e)	1.212 (kg/m^e)	2.28
Vent (project window)	5.60	4.28	1.32					1.32

Atmospheric conditions at the location of air flow meter during the test: Atmospheric temperature (T): 21.2 °C, Atmospheric pressure (B): 1023.0 hpa, Relative humidity: 25.2%

$Q_{st} = Q\,(W/W_s)^{1/2}$, $W = 3.485 \times 10^{-3}\,(B/(T + 273))$.

Q = airflow at non-standard conditions, $Q_s = Q_t - Q_e$.

Q_{st} = airflow corrected to standard conditions.

W_s = density of air at reference standard conditions − **1.202** kg/m^3 (0.075 lb/ft^3).

W = density of air at the test site, kg/m^3 (lb/ft^3).

B = barometric pressure at test site corrected for temperature, Pa (in.Hg), and

T = temperature of air at flowmeter, °C.

② Amount of spray water to live: 204 L/m^2 h,
③ Duration: 15 min,
④ Tolerance: no uncontrolled water leakage.

Water leakage was not detected under both static and dynamic pressure, and excellent water tightness quality was verified.

4 Conclusions

In this study, a new curtain wall system was proposed that could replace the aluminum cladding system used as the exterior skin material of the reinforced concrete high-rise building and was evaluated the structural and air/water tightness performance. The final results from this study are as follows:

1. The newly proposed cable-type curtain wall system is expected to reduce construction costs as a result of the reduction of construction period compared to the existing method.
2. The structural performance of cables against the design wind pressure was verified through a nonlinear analysis of the cable system.
3. Comparing the results of a nonlinear structural analysis of the proposed cable wall structural system with the results of a full-scale structural experiment shows similar results to the maximum load and displacement values, demonstrating reliable results.
4. For the positive initial tension applied to cables in the proposed cable system, 30% of the breaking force was considered most appropriate.
5. The air/water tightness demand performance of the proposed cable-type curtain wall system as a cladding material has been found to be suitable for ASTM E283, E331 and AAMA 501.1-05, thus it could be maximize energy efficiency.

Authors' contributions
HSP wrote the manuscript in consultation with JHW and WJC. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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