Typology of skybridges in Asia
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**ABSTRACT**
With the rapid development of high-density urban areas and the construction of high-rise complexes, the number of skybridges has increased during the last 20 years. While skybridges in high-rise building complexes have been attracting considerable attention, a few studies have been conducted on state-of-the-art skybridges, but not enough typological research on skybridges has been made based on actual cases. In this study, the typological difference among skybridges sharing common properties was verified using a statistical method based on the cases of skybridges in Asia. The completion year, length, width, and relative elevation of skybridges were used for the statistical analysis. Based on the results, six skybridge types, i.e., open circulation, open sky park, open programmatic, enclosed rooftop programmatic, enclosed circulation, and enclosed programmatic, and their characteristics were derived and described by a three-dimensional plot. This study provides a comprehensive understanding of skybridges, and it can be used as a reference material for researchers to understand how high-rise complexes with skybridges will evolve and change their urban environment. It will also help architects to design skybridges and communicate with clients and the public on their value.

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1. Introduction
The number of skybridges in high-rise complexes has greatly increased over the past two decades. Many Asian cities continue not only to expand their boundaries but also to develop many high-rise complexes in their city centers. The number of skybridges increases as the number of high-rises increases. According to a preliminary survey for this study, more than 100 skybridges were built as of October 2019 in approximately 60 high-rise complexes in Asian cities, and approximately 10 high-rise complexes were built with skybridges in 2020. The preliminary survey was conducted to determine the presence of skybridges in high-rise complexes in the CTBUH (Council on Tall Buildings and Urban Habitat) database because skybridges are most likely to appear in the same skyscraper complex, as Wood (2003) said. As of October 2019, 2,418 high-rise complexes were identified in the CTBUH database, nearly half of which (1,052) were in Asia. The inclusion of skybridges in high-rise complexes has been confirmed through web searches and online maps, except in a small number of cases. A total of 7,567 skyscrapers were built in the skyscraper complex, more than half of which were built in Asia, with 3,501 completed between 2000 and October 2019, indicating a significant increase in the number of skyscrapers built in Asia over the past 20 years.

The space located high above the ground is inevitably separated from the urban context on the street. Graham and Hewitt (2013) pointed out that the upper-class people’s desire for social separation is linked to the vertical encapsulation process. Harris (2015) and Graham and Hewitt (2013) introduced skywalk systems in Hong Kong and Mumbai as examples of the vertical separation in cities but not skybridges yet. However, the number of skybridges has rapidly grown with urbanization in the last two decades, which can be seen as a clear indicator of the upcoming development of urban verticality. The access to skybridges is much more controlled than that to skywalks. A skywalk is typically a space with surveillance and little control but given access to everyone. By contrast, a skybridge is a bridge connecting the vertical archipelago of the city center, which is not given access to everyone.

Harris (2015) identified four landscape modes and models of urban verticality. The new mode is associated with mega tall towers in Asia and the Middle East, which has been differentiated from the third model that has high-rise building blocks with multi-leveled urban circulation. Wood (2003)’s assumption, i.e., “Many of the conditions and problems to be overcome are the same once the ground plane is departed,” is based on the high-rise landscape vision that Ferris, Lang, and King had, whereas skybridges,
which are realized in Asia and the Middle East, have quite a different characteristic.

Skybridges, unlike skywalk networks in Hong Kong, Minneapolis, and Calgary, seem to focus on connections within high-rise complexes rather than strengthening urban connections, as noted by Wood (2003). As Graham and Hewitt (2013) pointed out, vertically separated spaces primarily seek to separate from the congestion on the ground. Skybridges connect skyscrapers, rather than reconnecting the separated vertical space to its urban context. They strengthen the connection between buildings in their complex, which can further distance the center of the vertical urban space from the ground and strengthen the vertical gated community. The study on skybridges will provide an opportunity to examine the status of urban verticality by connecting elements beyond simply looking at their technological features.

High-rise complexes are built based on concepts, such as vertical cities and compact cities, to enhance the innovative use of city areas through the integration effect of high-density areas (Al-Kodmany 2012; Al-Kodmany and Ali 2013; Hadi, Heath, and Oldfield 2018). However, living environments in high-rise spaces have not only positive effects but also negative effects, such as depression and community decline (Hadi, Heath, and Oldfield 2018; Hwang 2006; Parakh, Safarik, and Du 2018). To solve this problem, there have been increasing attempts to construct a ground-like environment in high-rise spaces, and skybridges are recognized as one of the methods to create a ground-like environment at elevation, along with sky gardens and sky courts. In Singapore, to solve the deteriorating quality of life due to the lack of such an environment in high-rise dwellings, the Housing and Development Board adopted ground-like spaces, such as skybridges, sky gardens, and sky courts, in the creation of community spaces (Hadi, Heath, and Oldfield 2018). Skybridges in other countries are often used for different functions, such as offices, stores, and hotels, rather than gardens and courtyards. They were mainly built for the synergistic effects of connecting buildings, creating special spaces, and improving seismic performance. In addition, skybridges, as outlined in previous studies (Wood 2003; Wood and Oldfield 2007), provide an alternative evacuation route and reduce redundancy associated with service supply, thus increasing the rental area ratio.

“Skybridge” has only recently been used as a term referring to bridge-shaped structures placed between high-rise spaces. This term is also commonly used to refer to urban pedestrian bridges installed at elevation (commonly referred to as a skywalk, skyway, or pedway) and bridges placed in mountain gorges. Because the term “skybridge” is ambiguous and has several different meanings, it is necessary to define the term “skybridge” for the purpose of this study. In this study, a skybridge is defined as “a substructure of a building that allows pedestrians to pass by connecting to another building at elevation.” In a preceding study, Wood and Safarik (2019) defined the term “skybridge” as “a primarily enclosed space linking two (or more) buildings at height,” but because this definition excludes the open-type skybridge, a new definition is required for the purposes of this study. The new definition follows Wood and Safarik’s definition in some respects but differs in detail. The interpretation of the definition is as follows: “a substructure of a building” means that the structure of a skybridge should be distinguishable from the structure of the buildings it connects. As many large-scale buildings have been built, the topology of buildings has also diversified, and buildings with void(s) in the center of the mass (e.g., OMA’s “CCTV Headquarters” and Zaha Hadid Architects’ “Opus”) and buildings with stacked blocks (e.g., OMA and Ole Scheeren’s “The Interlace”) have appeared. Some parts of these buildings connect to other parts of buildings, as do skybridges. However, it is difficult to distinguish the precise boundary of the space that can be defined as a “skybridge.” The characteristic “Allows pedestrians to pass” means that people must be able to pass from one node of the bridge to another node regardless of whether the passage is open to the public or not. Thus, bridge-like structures only structurally connect buildings or building parts and have no passage between the nodes of the structures. The characteristic “At elevation” means that a skybridge should be installed on the 6th floor or higher of the building to be distinguished from a skywalk, as defined by Wood and Safarik (2019).

The present study defines the types of skybridges and verifies the validity of the classification by assessing the characteristic differences of skybridges in high-rise complexes in Asia. It also attempts to enhance the classification of skybridges by deriving the general characteristics of each type. A skybridge is recognized as an important element to consider when planning high-rise complexes, as the number of high-rise complexes built along with skybridges is increasing. However, the research on the type and general characteristics of skybridges is insufficient. Four types of skybridges were suggested in the study of Wood and Safarik (2019): “enclosed circulation” (EC), “enclosed programmatic” (EP), “skylanes,” and “building-as-skybridge.” In a follow-up study (Wood, Du, and Safarik 2020), state-of-the-art cases for EC and EP types were analyzed in detail. However, in previous studies, the basic definition of a skybridge is based on having an indoor space, and subsequent studies have followed this definition. In this study, according to the proposed definition of a skybridge, open-type cases are also included, and new definitions are proposed to encompass these cases.
Statistical methods with variables from skybridges were used to validate the skybridge type classification. Statistical techniques allow easy determination of the appropriateness of skybridge type classification. In the process, the characteristics of each type can also be identified. However, this method requires careful consideration of the classification criteria and choice of variables to be used for verification. Moreover, some exceptional cases in a type require additional interpretation because the methodology itself does not determine the causal relationship between classification and variables.

To focus on recent cases, the regional scope of the survey was limited to Asia, where the construction of high-rise buildings is currently highly active. This research is an attempt to comprehensively understand the types of skybridges with varied characteristics. Subsequently, this study will benefit architectural designers to understand skybridges for their design practices and urban study researchers to understand the forthcoming phenomenon of vertical cities.

2. Materials and methods

In this study, the process of deriving the characteristics of the skybridge types consists of three steps: First, the classification criteria of the skybridge types were selected, and types were defined based on the criteria. Second, the types were verified through a statistical method. Finally, the general characteristics of the types were summarized. Skybridges have various classification criteria, such as function, envelope, structure, accessibility, and shape. In this study, envelopes and functions were used to create skybridge types. In the research by Wood and Safarik (2019), four skybridge types were introduced: EC, EP, skyplanes, and building-as-skybridge. “Skyplanes” and “building-as-skybridge” conflict with the definition of a skybridge presented in this study. The difference by type is verified using several variables related to a skybridge, such as the size and vertical position of the skybridge, construction year, function of the building complex, and climate. Accordingly, the Kruskal–Wallis test was used to verify the difference by type.

2.1. Data collection

The skybridges for which data were collected in the study were installed in 43 high-rise complexes in 13 Asian countries (Singapore, China, Malaysia, India, South Korea, Japan, Mongolia, North Korea, Indonesia, Kazakhstan, Cambodia, Thailand, and the Philippines). The list of skybridges was made based on the data of high-rise complexes up to October 2019 from The Skyscraper Center (CTBUH 2019), the largest high-rise database. In the list, 1463 complexes were identified as high-rise complexes built or being built in Asia as of October 2019, of which 43 were constructed with skybridges and 29 were under construction with skybridges.

Research data on the sample were obtained from research papers and web search data from Google, Naver, and Baidu. The qualitative data included the building envelope, function, and environmental context of the samples. The quantitative data included the completion year and exterior dimensions. The dimensions were measured using the length measurement tools of Internet map services, such as Google Maps, Naver maps, and Baidu maps, if no official data were available. The accuracy of the Internet maps has not been officially announced, but according to Wirth, Bonugli, and Freund (2015), the error of the relative length measurement values is in the range of 1.5 to 100 m; in the case of Google Earth, it is within 1%. The other Internet map services did not assess their accuracy, but in this study, they were regarded to have similar accuracy. Lengths in Internet map services are measured in meters, and the measured value is rounded to two decimal places.

If the shape of the skybridge is not rectangular, then the length and width values may vary depending on the measurement point, so the following criteria were applied in this study: The length of a skybridge was measured based on the distance between the center points of its edges where it meets buildings, and the width of the skybridge was measured at several points if there are changes in the width, and the average value is used.

Figure 1 is an example of measuring a skybridge with varied widths. The length of the skybridge in the example is 18.0 m, and the width is 4.0 m, which is the width of the equivalent rectangle. In this study, because there was no case of skybridges being excessively curved or radially connecting three or more buildings, the previous measurement standard was applied.

The Köppen climate classification of a city where a skybridge is placed was obtained using the longitude and latitude coordinates of the city with the kgc package of R (Bryant et al. 2017). The main climate classification, i.e., the capital character, was used in this study to avoid the complexity of interpretation.

Data from 109 skybridges were collected. Six skybridges with unknown functions and one skybridge (Marina Bay Sands), with an area too large compared to the others, were excluded from the study, and the remaining 102 skybridges were analyzed.

In the study, six qualitative variables and seven quantitative variables were collected (Table 1). “Envelope” and “Function” were used to create the skybridge type. Variables in the “Context” group were used to check the context for each skybridge type. Quantitative variables were used to verify the
2.2. Data description

Table 2 shows the results of calculating the statistics of the quantitative variables. “Cyear” shows skybridges that were mainly built in the last 20 years (range: 1985–2019, $M = 2011.62$, $SD = 5.41$). “Slength” and “Swidth” show the skybridge size variation (Slength range: 4.0–60.0, $M = 20.46$, $SD = 14.80$; Swidth range: 2.0–60.0, $M = 12.26$, $SD = 9.33$). “Sfloors” shows that most cases have a single floor (range: 1–4, $M = 1.22$, $SD = 0.57$). “Saspectratio” shows the ratio of length to width variation (range: 0.30–12.30, $M = 2.54$, $SD = 2.49$). “Sbase” and “Srel_elev” show that the floor on which the skybridge was built is the lower or upper floors (Sbase range: 6–58, $M = 25.36$, $SD = 12.12$; Srel_elev range: 0.25–1.01, $M = 0.67$, $SD = 0.22$).

The statistics of the entire sample show that many Asian skybridges were recently built, but the other variables are widely distributed; therefore, it is difficult to determine if the average of these values represents the general characteristics of all skybridges in Asia. Thus, the characteristics of skybridges must be assessed according to their type.

The frequencies of categorical variables are shown in Table 3. A large difference was found in the number of samples by country. Over 60% of the total cases were found in Singapore and China, and when the cases in Malaysia, India, and Korea were included, the combined cases exceeded 80% of the total. Although the Köppen climate classification values were investigated in detail, only the first letter of the large classification was used in the analysis, as the number of samples greatly varied for each detailed climate classification, and the larger values of the categorical variables became more difficult to interpret. There were 58 cases of tropical climate, 4 cases of the arid climate, 21 cases of temperate climate, and 19 cases of continental climate. In the complex functions, there were 61 residences, 12 offices, 3 hotels, and 20 mixed. Four values were found for the envelope-type variable, depending on whether a skybridge is indoors or used on a rooftop. However, among the 47 open types, none were on a rooftop. In the enclosed type, 42 cases were not used on the roof and 13 cases were used on the roof. The main function of the skybridge was circulation, with the highest number of 40. Sky park scored 34, amenity 22, residence 3, office 2, and hotel 1. Circulation- and sky-park types without specific programs accounted for more than 70% of the total cases, and less than 30% were those with specific programs.

From the frequency table, it was confirmed that the distributions of values for the country and climate, use of the building complex, and main use of the skybridge were uneven. Values that indicated relatively high frequency were as follows: country – Singapore, climate – A (Tropical), complex function – residence, main function – circulation.

2.3. Skybridge typology

Skybridge types may differ by the subject of study. As this study focuses on the spatial aspect of skybridges, the type was made by spatial classifications. The classification criteria of skybridges covered in this study include their envelopes and functions. The envelope is related to the features of the enclosure of a skybridge. A skybridge is typically a box-shaped structure that connects a building to another building linearly; its envelope consists of a floor, a roof, and two side walls. The floor is an essential part of a skybridge, but a roof and two side walls are not necessary. The roof can be classified into two types, i.e., with and without a pedestrian walkway on the top. The combination of the floor, roof, and wall creates six classifications, but in real cases, it creates only the open type, enclosed type, and enclosed with a rooftop type.

The functions of a skybridge are classified into three categories and used for the analysis in this
study. If the function of a skybridge is for simple passage, it is classified as a circulation; if it has no distinct function and has a green space, it is classified as a sky park; and if it has an assigned specific program, it is classified as programmatic. The skybridge type was composed by combining the envelope and function of the skybridge. Because the skybridge function classification is three and the envelope classification is also three, then nine combinations can theoretically appear, but only six combinations were confirmed in this case. The type combinations shown in the cases are shown in Table 4, and the type names, abbreviations, number of cases, and representative cases are also presented.

Skybridge types include open circulation (OC), open sky park (OS), open programmatic (OP), enclosed rooftop programmatic (ErP), EC, and EP. In the open type, all functions appear. All 11 OC cases connect the buildings’ sky gardens, and both OP cases have a swimming pool. In the ER type, the programmatic function type appears in only 13 cases. Unlike other types, the ErP type included the enclosed and open spaces in one skybridge. In the enclosed types, 29 cases of EC and 13 cases of EP appear, and no cases with the sky park function appear.

Other skybridge properties, such as structure, accessibility, and shape, can affect its spatial aspects. However, the review of cases found that these properties were not valid enough to define the skybridge types. These properties may be valid in studies that focus on other aspects of skybridges, such as structural, geopolitics, and morphological aspects.

### 2.4. Skybridge type and context

Mosaic plots were drawn to identify the types of skybridges that mainly appear, according to context (Figure 2). In the mosaic plots, the area of a box represents the ratio of one type to the total number of cases. The frequency of climate by the skybridge type is shown in Figure 2 (left). In the figure, it is confirmed that the types of skybridges built according to climate are different. The open types (OC, OS, and OP) appear only in the tropical climate, the ErP types mainly appear in the tropical and temperate climates, and the enclosed types (EC and EP) are more common in temperate and continental climates. However, the proportion of continental climate is greater in the EP type. The dry climate cases are all EC types, all from Mongolia’s “Max Elite” residence complex.

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3Structural properties: The size and spatial features of a skybridge can be different depending on its structural properties, which can also serve as a criterion for the classification of skybridge types. The structural properties include the structural materials of a skybridge and connected buildings and damping systems of the buildings. The structural materials of 71 cases out of 102 cases in the study are concrete, the structural materials of 6 cases are composite, and only one is steel. The structural materials of 64 skybridges are steel, and the rest of them are concrete. All the concrete skybridges are in the concrete buildings.

Accessibility: The restricted access to a skybridge may be an important feature. A skybridge is generally considered to have difficult public access, unlike most skyscrapers, but due to the limitations of data, it is not possible to determine how many skybridge allows public access.

Shape: The shape of a skybridge was identified by photographs. Most of the cases were rectangular or close to rectangular, so they could not be classified by the difference in their shape.

4An 18-story building in the residential complex was included in the CTBUH skyscraper list. This may be because the skyscrapers defined by the CTBUH include buildings that are significantly higher than surrounding buildings.

| Table 1. Study variables. |
|---------------------------|
| **Category** | **Variable name** | **Description** | **Type** |
| Categorical Variable | Climate | Country code | Nominal |
| Categorical Variable | Country | Köppen climate classification | Nominal |
| Categorical Variable | Func_main | Main function of a tall building complex (levels are below) | Nominal |
| Envelope | Senclosed | Enclosed or not | Binary |
| Envelope | Srooftop | Skybridge rooftop as a sky space | Binary |
| Function | Sfunc | Main function of a skybridge (levels are below) | Nominal |
| Quantitative Variable | Time | Completion Year | Discrete |
| Quantitative Variable | Elevation | Lowest building floor connected to a skybridge | Discrete |
| Quantitative Variable | Cyear | Relative elevation of a skybridge to the average floor number of connected buildings | Numeric |
| Quantitative Variable | Srel_elev | Skybridge length between buildings | Numeric |
| Quantitative Variable | Sleng | Skybridge width | Numeric |
| Quantitative Variable | Swidth | Number of skybridge floors | Discrete |
| Quantitative Variable | Sfloors | Skybridge length/skybridge width | Numeric |
Table 2. Summary of quantitative variables.

| Category | Variable | n  | NA | min | max  | mean | median | SD  |
|----------|----------|----|----|-----|------|------|-------|-----|
| Time     | Cyear    | 102| 0  | 1985| 2019 | 2011.62 | 2011 | 5.41 |
|          | Swidth   | 102| 2  | 2   | 60   | 12.26 | 12    | 9.33 |
|          | Sfloors  | 102| 1  | 4   | 4    | 2.22  | 1     | 0.57 |
|          | Saspectratio | 102| 0  | 0.3 | 12.3 | 2.54  | 1.7   | 2.49 |
| Elevation| Sbase    | 102| 6  | 48  | 25.36 | 32.5  | 32.5  | 12.12 |
|          | Sel_elev | 102| 0.25| 1.01| 0.67 | 0.68 | 0.22 |

Table 3. Frequency table of skybridge categorical variables (all total n = 101).

| Variable | Value (3 distinct values) | n  | %  | Cum. % | Value (4 distinct values) | n  | %  | Cum. % |
|----------|---------------------------|----|----|--------|---------------------------|----|----|--------|
| Country  | SG (Singapore)            | 37 | 36.3 | 36.3  | Climate (4 distinct values) | A (Tropical) | 58 | 56.9 | 56.9  |
|          | CN (China)                | 26 | 25.5 | 61.8  | B (Arid)                  | 4  | 3.9 | 60.8  |
|          | MY (Malaysia)             | 8  | 7.8 | 69.6  | C (Temperate)             | 21 | 20.6| 81.4  |
|          | IN (India)                | 6  | 5.9 | 75.5  | D (Continental)           | 19 | 18.6| 100.0 |
|          | KR (South Korea)          | 6  | 5.9 | 81.4  | Residence                 | 60 | 58.8| 58.8  |
|          | JP (Japan)                | 4  | 3.9 | 85.3  | Office                    | 19 | 18.6| 77.5  |
|          | MN (Mongolia)             | 4  | 3.9 | 89.2  | Hotel                     | 3  | 2.9 | 91.4  |
|          | KZ (Kazakhstan)           | 3  | 2.9 | 92.2  | Mixed                     | 20 | 19.6| 100.0 |
|          | ID (Indonesia)            | 3  | 2.9 | 95.1  | Skybridge main function (6 distinct values) | Circulation | 40 | 39.2| 39.2  |
|          | KH (Cambodia)             | 2  | 2.0 | 97.1  | Sky park                  | 34 | 33.3| 33.3  |
|          | KP (North Korea), PH      | 3  | 2.9 | 100.0 | Amenity                   | 22 | 21.6| 94.1  |
|          | (Philippines)             |    |    |        |  |          |  |  |  |
|          | TH (Thailand)             |    |    |        |  |          |  |  |  |
| Elevation| Open                      | 47 | 46.1| 61.8  | Residence                 | 3  | 2.9 | 97.1  |
|          | Enclosed                  | 42 | 41.2| 87.3  | Office                    | 2  | 2.0 | 99.0  |
|          | Enclosed rooftop          | 13 | 12.7| 100.0 | Hotel                     | 1  | 1.0 | 100.0 |

Table 4. Skybridge type by function and envelope.

| Envelope | Function | Type Name (abbreviation) | n   | Representative Case |
|----------|----------|--------------------------|-----|---------------------|
| Open     | Circulation | Open Circulation (OC) | 17  | The Tembusu(SG), Fusionopolis(SG) |
|          | Sky park | Open Sky park (OS) | 34  | SkyTerrace@Dawson(SG), The Pinnacle@Duxton(SG) |
|          | Programmatic | Open Programmatic (OP) | 2  | Sky Habitat(SG), Starview(TH) |
| Enclosed | Roof top | Enclosed Roof top Programmatic (ErP) | 13  | Tencent Seafort Towers(CN), Shum Yip Upperhills(CN), D-Cube City(KR) |
|          | Circulation | Enclosed Circulation (EC) | 29  | Petronas Towers(MY), Yongsan Rex(KR) |
|          | Programmatic | Enclosed Programmatic (EP) | 13  | Linked Hybrid(CN) |

Figure 2. Skybridge type-climate (left); skybridge type-complex main function (right).

In tropical climates, the open type, especially the skybridges with the sky park function, mainly appears, which may be due to bad atmospheric conditions on the ground in hot climate regions, as noted by Wood (2003), Graham and Hewitt (2013), and Harris (2015). Open skybridges provide an alternative ground on high floors to increase natural ventilation and access to cool places. Contrary to the skybridge cases of tropical regions, enclosed types are most commonly found in temperate and continental regions. This trend clearly shows that the skybridge envelope responds to the climate.

Figure 2 (right) shows the frequency of the main functions of the building complex according to the type of the skybridge. From the figure, there is a difference in the type of a skybridge built according to the function of the building complex. The open types (OC, OS, and OP) mainly appear in residential complexes; the ErP type appears in residential complexes, office complexes, and complexes; and the EC type mainly appears in residence complexes and office complexes. The EP type mainly appears in mixed complexes and appears slightly less frequently in hotel complexes, office complexes, and residential complexes.
complexes. The skybridges in the hotel complex are of the EP type, which are mainly used as guest rooms.

Interestingly, the majority of the open-type skybridge’s complex functions are residential, and the residential complex has few programmatic-type skybridges. Half of the six programmatic skybridges in the residential complex are residential, the open type has a swimming pool, and only one of the encl+rt types has amenity functions. This may be because the cost and benefit of the programmatic skybridge are considered insignificant in the residential complex. By contrast, in office complexes and mixed-use complexes, the proportion of programmed skybridges is large, indicating that the skybridge function is affected by the function of the high-rise building complex.

2.5. Kruskal–Wallis test

The Kruskal–Wallis test was performed on the quantitative variables to check whether there was a significant difference between the types. The Kruskal–Wallis test is a method of performing a one-way analysis of variance using rank. Because it does not require parameter assumptions, it can be used for the analysis of quantitative variables that have a small number of samples and do not satisfy normality. Most of the quantitative variables collected in the study do not satisfy normality, and when the samples are grouped by type, the number of samples of the OP type is less than 10. The grouping of the variables was used as the skybridge types, as identified in Table 4.

If the results of the Kruskal–Wallis test indicated a significant difference between groups, then pairwise comparisons were performed using Dunn’s test (1964) as a post-hoc test to determine which groups that had significant differences. Because the test using the rank sum cannot account for the difference due to the magnitude of the original measured values, violin plots were created to confirm this difference. R 4.0.2 version (R Core Team 2020) was used for the Kruskal–Wallis test, and ggstatsplot (Patil 2018) and vioplot (Adler and Kelly 2020) were used for Dunn’s rank sum pairwise comparison and data visualization.

2.6. Skybridge 3D plot

In the Kruskal–Wallis test, differences according to types were checked for each variable, so it was difficult to comprehensively examine the characteristics of each type of skybridge. The quantitative variable is the size and vertical position of the skybridge, ignoring the construction year. Because all skybridges in the study are rectangular or similar in shape, each case can be expressed in a box shape based on the measured values.

When drawing the box, the width and length were measured using the metric system, and the thickness is the number of floors multiplied by 4. However, because the open type does not have an indoor space, it is expressed as a square plane with no thickness. The box is placed at the corresponding value on the z-axis according to the relative elevation of the skybridge. Color mapping was applied according to context variables (climate and complex main function) to indicate whether there was a difference according to the context in the characteristics of each skybridge type. Rhino 6 grasshopper (McNeel 2017) was used for drawing skybridge boxes by type.

3. Results

3.1. Kruskal–Wallis test

In the results of the Kruskal–Wallis test, differences according to types were found in all quantitative variables. The test statistics (\(H\)) of degrees of freedom, and p-value for each variable can be found in the comparison figure for each variable. For each variable, a post-hoc test was performed using Dunn’s method to determine which group combinations showed differences, and the significant results are presented in the chart for each variable. The significant differences appearing according to the comparison of the average rank among groups are as follows: [EC, EP, OS] – [ErP, OC] for the completion year (Cyear); ErP – all the other types for the skybridge floor number (Sfloors); EP–OC and EP–OS for the skybridge length (Slength); EC–ErP, EC–OS, ErP–OC, and OC–OS for the skybridge width (Swidth); EC–ErP, EC–OS, EP–OS, and OC–OS for the skybridge ratio of length to width (Saspectratio); and EP–OC for the relative elevation (Srel_elev).

3.2. Variable plots by skybridge type

In the violin plot, the differences between groups and the distribution of data by type were identified. Along the X-axis of the violin plot, the skybridge type and the number of samples are displayed, and dots representing the samples are arranged on the Y-axis. The estimated kernel density was plotted according to the sample density. Near the center of the density plot for each type, a red dot representing the mean of the sample and its value is displayed. Outliers are represented in gray dots, and a label indicating which building complex is installed. Above the canvas area, the results of the Kruskal–Wallis test are displayed, and lines indicating the group pair showing a significant difference and the significance probability are displayed in the upper area of the canvas.

Significant differences in the completion year were found between the early groups (EC, EP, and OS) and later groups (ErP and OC). Although EC, EP, and OS
were in a group, the EC has a relatively wider range of completion years (Figure 3), and EP and OS began to be popular around 2010. Because of the late emergence of the other types than EC, it is not odd that Wood (2003) defined a skybridge as “a primarily enclosed space.” Hence, a new definition of a skybridge is suggested in the introduction of this paper.

Significant differences in the number of skybridge floors were found between the ErP and the other types. There are cases of the ErP type from a single floor to four floors, but OS, OC, and CP types were all built as a single floor, and EC and EP types are mostly single floors (Figure 4). The five skybridges of “Hangzhou Civic Center,” which are outliers of EC, differ only in length from the other skybridges of the same building complex that appears as an outlier of EP. The EP of Hangzhou Civic Center is used as a conference room, whereas the others are classified as EC because there is no special program although they have the same spatial capacity as EP’s. The mismatch of the function and type may be a consequence of an over-design.

Significant differences in the length of the skybridge were found in EP–OC and EP–OS. In addition, when comparing the length distribution of skybridges by type, the difference in the value range could be confirmed (Figure 5). OC and OS have a smaller average
length and narrower value range than EC, EP, and ErP. The OP has a small number of cases, so no significant difference from other types was verified. The OP has a longer length compared to the other types because in all cases, a pool of sufficient length has been installed. There is an outlier with a length of 100 m in ErP, which is the skybridge of the “Atmosphere” building in Kolkata, India. A swimming pool is installed on the roof of this skybridge, as in the case of the OP. The spatial capacities of programmatic types are varied by their functions in detail. Thus, the segmentation of functional classification may be needed as their number increases.

Significant differences in the skybridge width were found in EC–ErP, EC–OS, ErP–OC, and OC–OS. In the circulation function types (EC and OC), the width is narrow, and the width varies depending on the function (Figure 6). There are outliers over 10 m in width in the EC. One of them is used as a passageway, and the observation deck at “Nina Towers” in Hong Kong, China, and the others are only used as aisles at “Hangzhou Civic Center” in Hangzhou, China. If the function is inserted into the skybridges of “Hangzhou Civic Center,” then it can be an example of the EP type. Excluding outliers, the EC cases are not wide enough to insert functions other than passages. The EP, ErP, and OS have similar average lengths and length ranges.

Figure 5. Multiple comparison of skybridge length by skybridge type.

Figure 6. Multiple comparison of skybridge width by skybridge type.
The OC does not show any outliers and, like the EC, only has enough width to be used as a passage. The ErP’s outliers are over 50 m wide, and they were built in 2017 at the “Tencent Seafront Towers” in Shenzhen, China.

Significant differences in the skybridge ratio of length to width were found in EC–ErP, EC–OS, EP–OS, and OC–OS. The ratio of length to width increased in the order of OS < ErP < OP < OC < EP < EC, but this order was different from the average length order by type (Figures 5 and 7). The ratio of length to width tends to be shorter if the skybridge has outdoor spaces or functions other than circulation. EC has a very wide length-to-width ratio compared to the other types because the length of the EC-type skybridge varies, whereas the width is mostly narrow.

Significant differences in the relative elevation of the skybridges appeared only between the EP and OC. Most of the ranges of the relative elevation appear from the lower middle to the upper part of the buildings, but the EP appears only above the middle of the building (Figure 8). The OP appears only at the top of the building. The function of the OPs is a pool, so they are mostly built at the top. Wood (2003) mentioned that the middle part of a building would be a suitable location for a skybridge just as Petronas Towers, but this view may be centered on the evacuation load. In actual cases, the average vertical location of

Figure 7. Multiple comparison of skybridge ratio of length to width by skybridge type.

Figure 8. Multiple comparison of relative skybridge elevation by skybridge type.
a skybridge is higher than that of the middle point of the building, and significant differences are observed in the vertical location and distribution according to the type.

### 3.3. Characteristics of skybridge types

The difference between types was verified in the Kruskal–Wallis test and Dunn’s pairwise comparison, and accordingly, the characteristics of each type, as shown in Table 5, can be derived with quantitative variables. There are 29 cases of EC, which appear relatively large in various climates and building complex functions. Most of the construction dates were from 2000 to 2017. Such cases were mainly built as single-story buildings with lengths ranging from 4 to 58 m, varying from short to long, and most of the widths are narrow, from 2 to 6 m. Their length-to-width ratio ranges from 1.2 to 12.3, showing a wide range of lengths. The relative elevation also ranges from 0.33 to 1.00, and the distribution is even.

There are 13 cases of EP, mainly in continental-climate and mixed-use building complexes. Most of the construction dates are from 2009 to 2017, which are the latest. They are mostly single-story.sets, their lengths range from 14 to 43 m, and their widths range from 6 to 24 m. Their length-to-width ratio ranges from 0.9 to 6.6. The relative elevation ranges from 0.60 to 1.00, and the majority are built above the waist of the buildings.

There are 13 cases of ErP in the tropical, temperate, and continental climates. The construction dates are from 2011 to 2019, and the number of floors ranges from 1 to 4. There are many double-story cases, with a length of 7–60 m. Their widths range from 7 to 28 m with two outliers of approximately 50 m. The length-to-width ratio is small, from 0.6 to 3.8. The relative elevation ranges from 0.39 to 0.91 and appears even from low to high.

There are 11 cases of OC in residential and office complexes in the tropical climate. The construction dates of the cases are from 2018 to 2019, which is more recent than that of the EC. Most of the cases have similar characteristics to the EC cases, except for the fact that all of them are single-stories.

There are 34 cases of OS, many of which are in residential complexes in the tropical climate. The construction dates are from 2009 to 2016, and all of them are single story, with a length of 4 to 32 m and a width of 9 to 23 m. The length-to-width ratio is small, ranging from 0.3 to 2.9, and the relative elevation ranges from 0.25 to 1.00.

Only two types of OP appear in the residential complexes with tropical climates, all used as swimming pools. All were built in 2015 and are single-stories, 27 and 43 m long, and 9 and 16 m wide. Their length-to-width ratio is between 2.7 and 2.9, and their relative elevations are between 0.90 and 1.00. Their number is small, so it is difficult to say that this is a general characteristic of the OP type.

Cases of EC, EP, and ErP, which have wide widths, appear in the office complexes in temperate climates. Six skybridges in “Hangzhou Civic Center” (e.g., EC-5 and EP-1) and two skybridges in “Tencent Seafront Towers” are more than 60 m wide, which are much wider than in any other cases. The EC-type skybridge of “Hangzhou Civic Center” is not significantly different from that of the EP-type skybridges in terms of its outer shell and size. The EP type is used as a conference room, and the EC type is used only as a passage, so other programs can be inserted later. The skybridge of “Tencent Seafront Towers” seems to be reasonable as a pioneering case, which suggests the development direction of the “programmatic” type rather than as an exceptional case of the ErP type. Ward, Ding, and Etherington (2018) explained that the building’s skybridge involves a library and sports facility on both skybridges to “promote innovation in a dense urban context.”

The ErP-type skybridge installed in the “Atmosphere” is the only case that is 100 m in length. The “Atmosphere” is a luxury residential complex, and its skybridge is used for residential facilities and swimming pools. This skybridge case is not installed in or on the top floor of the building. It has a very long indoor space and actively uses the roof space. Moreover, it is

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**Table 5. Summary of quantitative variables by skybridge type.**

| Type | Range | Cyear | Sfloors | Slength | Swidth | Saspectratio | Srel_elev |
|------|-------|-------|---------|---------|--------|-------------|----------|
| EC   | 1994–2017 | 1–2   | 4.3–58.4 | 2–24 | 1.2–12.3 | 0.33–1.01 |
| EP   | 2009–2015, 62 | 1.24(0.44) | 22.43(16.55) | 7.43(7.86) | 4.34(3.52) | 0.70(2) |
| ErP  | 1985–2017 | 1–2   | 14.5–43.3 | 5.5–24 | 0.9–6.3 | 0.6–1 |
| OC   | 2008–2019 | 1–1   | 6.7–20.6 | 3.6–4.4 | 1.9–4.7 | 0.33–0.97 |
| OS   | 2015–2019, 14 | 1–1   | 11.5(15.38) | 3.89(0.31) | 2.91(1.09) | 0.51(0.22) |
| OP   | 2011–2015, 7 | 1–1   | 54.8(3.39) | 16.34(3.71) | 1.02(0.68) | 0.62(0.24) |

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Figure 9. Skybridge 3D plot by type with color code of climate.

Figure 10. Skybridge 3D plot by type with color code of complex main function.
similar to “Marina Bay Sands,” except that it has an indoor space.

3.4. Skybridge 3d plot

A skybridge was drawn in a 3D space according to its parameters (Figures 9 and 10). One box corresponds to one case. The length, width, and thickness of the box are drawn according to the length, width, and number of floors. The open skybridge is represented as a plane box. The box was placed on the z-axis according to the relative elevation of the skybridge. The box was colored according to the context in which the skybridge was placed.

In Figure 9, the characteristics of skybridges appear by type in addition to the climate. Outliers are easily identified in the figure for the EC. Similar boxes are shown in the figure of the EP, all of which are skybridges in the “Hangzhou Civic Center.” These cases have a large space even when compared to the general case of EP. As shown in the ErP figure, the scale of the ErP skybridge exhibits large variations. The difference in the size of the skybridges according to the climate was confirmed, but there are many large-scale skybridges in the temperate-climate category. All open-type skybridges appear in the tropical climate category, and the majority are not very large. In most cases of continental climate, the size of the skybridges was small, and the length-to-width ratio was large. Cases of dry climate appear only in EC and are short and narrow, but the number of cases is too small to confirm their representativeness.

In Figure 10, the characteristics of skybridges by type are shown, including the main function of the building complex. Skybridges with large spaces mostly appear in office complexes, most of which are examples of temperate climates (Figure 9). In the cases of the mixed-function complex, skybridges with large spaces do not appear. Cases of residence complexes appear in all types, but there are many OS types. All cases of hotel complexes appear in EP, and they have a medium-sized space, but they cannot be directly generalized because of the small number of cases.

4. Discussion and conclusions

This study attempted to define new skybridge types based on the spatial type and function by examining different skybridge cases and comparing the actual case of skybridges and the existing definitions from the literature. Skybridges are expected to be developed in many global cities where urban verticality is slowly realized. The definition and type classification of skybridges are necessary because they can help people to understand the characteristics of urban verticality. In the study, tropical skybridges were realized as open alternative grounds required as a response to the tropical climate pointed out by Wood (2003), Graham and Hewitt (2013), and Harris (2015).

By contrast, unlike the future city vision of Wood (2003), skybridges have not seem to be developed into an urban connection by exceeding the regional connection between high-rise buildings. As Harris (2015) classified, the new urban verticality emerging in Asia is distinct from the 20th-century modernist urban appearance referenced by Wood (2003). Skybridges are only involved in the inner connection and have a higher relative elevation than the middle part of a building, which may be evidence of the development of the vertical separation of the city. To clarify these changes, a study on skybridges focusing on urban verticality should follow.

In this study, it was confirmed by the Kruskal–Wallis test that the proposed types of skybridges are suitable for classification, and the difference between the types and distribution of variables was confirmed by the Dunn’s test and violin plot. Skybridge characteristics by type were visualized in a 3D space for a comprehensive understanding. Although there have been significant findings obtained through statistical methods in this study, these should be accepted within the following limits: If the variables used to verify the classification are not suitable, then the classification may appear to have failed regardless of the validity of the classification. Because the research subject is limited to Asia, whether the general characteristics of skybridges found here will appear in other regions is not known. To complement this, research-based on cases from around the world is required. Because there was only one high-rise building database used as the basis for constructing the sample list for the study, the number of samples may have been insufficient, or there may have been a bias in the sample group. To compensate for this problem, other high-rise-building databases can be used, or cases not included in the database can be included in the research. Because it was difficult to check all the buildings in the database, skybridges installed in a single building that is not a part of a building complex were not included in the study. Regardless of these limitations, this study will help to develop a new building typology and to understand the general characteristics of skybridges.

In sum, this study suggests the types of skybridges and derived the characteristics of each type in high-rise complexes in Asia. The six skybridge types derived from the building envelopes and functions are OC, OS, OP, ErP, EC, and EP. The findings confirmed through statistical methods that the completion year, size, ratio of length to width, and relative elevation of skybridges differ among types. The characteristics of each type are shown comprehensively in a 3D space in Figures 9 and 10. Differences appearing according to the context of the skybridges were also confirmed. In particular, the open types (OC, OS, and OP) only appear in the tropical
climates, and the enclosed types (EC, EP, and ErP) of the large skybridges appear in office complexes in temperate-climate regions. In some types, outliers that do not follow the general characteristics of the type have appeared, and these are understood as pioneering cases that need to change function or suggest the direction of the development of the type. Furthermore, this study provides a framework for a comprehensive understanding of skybridges in Asia and presents the characteristics of skybridges by type. The results of this study can be used as reference material for researchers to understand how high-rise complexes with skybridges will evolve and modify their urban environment. It will also help architects to design and, more importantly, to communicate with clients and the public when they consider introducing skybridges in architectural design and high-density urban planning.

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