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A Study on Predicting the Movement of Columns in Hanok Architecture Using the UMAP and DBSCAN Algorithms

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Abstract: A hanok is a traditional Korean house built with wood as the main structural material. It is constructed using cross- and unidirectional joint techniques without the use of steel. A hanok is composed of vertical and horizontal members, with columns being the most important vertical members and Daedeulbo being the most important horizontal member. As a cultural heritage structure, a hanok is often deformed due to damage to the wood over the years. In particular, the building beginning to lean is a typical example. Depending on the extent of damage, hanoks are repaired through partial or complete dismantling, but the same phenomenon recurs in many hanoks even after repair. In this study, 69 hanoks with well-documented records were selected to build a building column arrangement DB, column movement DB, and building attribute DB. The constructed DB was optimized in two dimensions by utilizing the features of each element with the UMAP algorithm and then clustered using the DBSCAN algorithm. Using this method, the movement of one column was analyzed individually, and the movement of two, three, and four columns was analyzed in groups, considering the characteristics of a hanok. As a result, similar patterns of column movement were found in hanoks with similar shapes. It was also possible to identify vulnerable locations according to the direction of column movement, and it was found that the deterioration of the joining strength of horizontal members affects the movement of columns.

Keywords: hanok architecture; hanok column; column movement; UMAP; DBSCAN; Korean cultural heritage

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1. Introduction

A hanok is defined in the dictionary as "a house built in a unique Korean style as compared to a Western style building". According to Article 2 of the Act on the Promotion of Architectural Assets such as Hanok (Law No. 12739, enacted on 4 June 2015), "hanok" refers to a building that reflects the traditional style of Korea, with the main structure being wooden, with columns, beams, and a Korean-style roof frame. Additionally, "hanok architectural style" means a building that has the form and structure of a hanok or is built using modern materials and technologies.

Unlike Western-style wooden buildings, Hanoks are constructed with cross- or unidirectional joints without the use of iron. Even when the columns are erected on the foundation, they are not adhered, but crossed or unidirectionally jointed, and this technique plays a role in preventing the deformation of the building by making the load on the roof heavier. However, when the heavy self-loading of the top is not evenly distributed throughout the wood structure, it causes twisting, leaning, and other deformations [1].

Regarding Korea's hanok cultural heritage, a "periodic inspection" was established in Article 44 of the Cultural Property Protection Law Act of 2006 to find risk factors at an early stage and encourage follow-up to prevent damage before major deformation and damage occurs.

Periodic inspections are an important indicator of the overall condition of a building. It is possible to identify cultural properties that are in urgent need of repair, and repairs can be carried out immediately with simple methods.

However, the limitation of periodic inspections is that they consist of visual inspection indicators and do not have numerical evaluation indicators, so, by the time the column movement of a hanok is visually detected, the best time to rectify the issue has passed (Figures 1 and 2).

Figure 1. Steel supports to prevent the column leaning phenomenon. This hanok's columns were leaning outward, and steel supports were installed to prevent further leaning. As of 2016, the hanok has been completely dismantled and repaired. The cause is unknown. (National treasure: Yeosu Jinnamgwan).

Figure 2. Columns leaning to the left. The upper part of the column is visibly leaning to the left. The cause remains unknown. (Treasure: Wanju Wibongsa Bogwangmyeongjeon, taken in 2018).

When repairing an entire building that is leaning to one side, it is not enough to straighten the columns if it is an old building. There is a requirement for measuring and investigating in the cases of structures that have Gwisoseum and Anssollim. In addition, the subsidence or protrusion of foundation stones should be analyzed in detail and repaired after the presence or absence of Gwisoseum and Anssollim is determined [2].

One of the main reasons for the structural failure of Geunjeongjeon, a hanok building located in a palace as a representative building of Korean cultural heritage, was determined to be an excessive load on the roof, and a plan to reduce the roof load was studied [3]. In order to solve the problem of roof load in repairing hanok architecture, the method of hollowing out the roof to reduce the weight or the Deotgeori method, which modifies the internal structure of the roof to reduce the load on the roof area, was applied. However, the problem was pointed out in a situation where the structure's shape was changed only for the part that reduces the load. Although the overall load was reduced by changing the roof structure with the Deotgeori method, the load in certain parts was increased, so the balance of the roof changed, indicating the problem of additional damage [4].

It was pointed out that there are problems with the construction process and method, problems with the recording and documentation process, and problems with the repair regulations in repairing defective hanok architecture [5]. In particular, defective hanok architecture has a tendency to cause secondary defects even after repair, and these problems constantly recur.

Hanok architecture, which is registered as a cultural heritage in Korea, is required to report on the repair process and results. However, in many cases, there are no detailed records of the repair history, and even recently published repair reports do not clearly explain the cause of the repair, so the analysis of individual repair causes is fragmented [6].

The most difficult part of reviewing the structure of a hanok is processing the member, location, and joint data in structural analysis software to perform interpretive modeling. In the case of a hanok, there are many complex and intertwined structural members to be modeled, so it is not an easy task to perform interpretive modeling [7].

In old hanok buildings, new and old members are combined during the restoration process, which makes structural calculations more difficult and limits the ability to identify the cause of column movement.

In this study, the column movement and architectural attribute data of 69 hanoks among Korean cultural heritage buildings were extracted. The defects of hanok architecture cannot be attributed to a single cause. Even if the primary problem is solved, a secondary problem may arise because hanok architecture is characterized by a connection with small members. This study focused on the movement of the columns, which are the main structure of hanok architecture. Although the structural problems of hanok architecture are complex, the biggest defect is column leaning, which can be seen as a step before the collapse of the building, so the study of column movement was conducted by taking a reverse approach.

Similar hanoks were classified to derive the movement patterns of columns. The process of deriving the movement patterns of the columns was carried out in stages by analyzing the columns by location, considering the characteristics of the hanok's cross- or unidirectional joints. By deriving the common problems of hanoks, it is expected that the problems of the building itself can be found in advance before they are visually detected and appropriate and new repair methods can be developed.

2. Theoretical Considerations

2.1. Deformation and Damage of Hanok

When two materials are joined in the same direction, this is called a unidirectional joint, and when two materials are joined at an intersection or diagonal to each other, this is called a cross joint [2].

Cross- and unidirectional joints are collectively referred to as joints. A structure made by joining several members is called post-and-beam construction, and a hanok is a representative building. By applying the joint technique, a hanok is built without using even a single nail. It can be said that it is an architecture that combines economy and aesthetics with technology that is not far behind modern science and technology.

Depending on the location of the members that make up a hanok, there are various cross- and unidirectional joint techniques by region, such as a Teok cross joint, Bitteok cross joint, Sagae cross joint, Sambunteok cross joint, Jumeokjang unidirectional joint, Jangbu unidirectional joint, and Teoksol unidirectional joint (Figures 3 and 4).

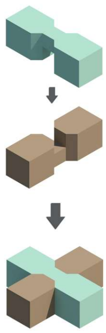

Figure 3. WangJji cross joint. This is the WangJji cross joint, which joins two members by intersecting them.

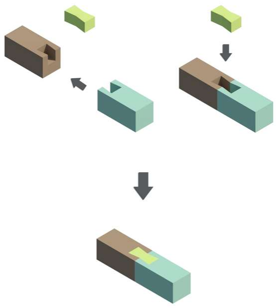

Figure 4. A butterfly unidirectional joint. Since the length of the wood is limited, two members are joined in the same direction. A groove is carved between the two members, and a piece of wood of the same shape is inserted into the groove. This shape is called a butterfly joint because it resembles the shape of a butterfly.

The joining shape can make a big difference in the strength of the connection among the members, and it is used in a variety of ways to ensure a strong connection, or for a neat finish [8].

Due to the nature of wood, material, structural, and environmental factors cause deterioration in performance after a building is constructed. As a result, the cracking, twisting, leakage, subsidence, displacement, deformation, and collapse of wooden building members occur, and the durability of the structure is reduced [5].

When cultural heritage is heavily deformed and damaged, dismantling is carried out, which often results in most of the cross joints being twisted and cracked, or the unidirectional joints being worn and separated. Their connection among materials is reduced (Figure 5). In particular, when using unseasoned lumber, the performance of the joint is significantly reduced due to shrinkage and expansion of the wood, which is the main cause of reduced joint strength [9].

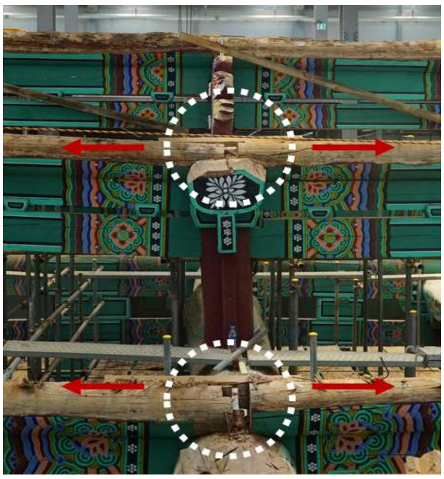

Figure 5. Horizontal members with ongoing separation. The horizontal members are placed on the columns using a unidirectional joint technique. This technique involves a butterfly joint, but the member joined to the groove is damaged, and the two horizontal members (white circle) undergo separation (red arrow). If they move in different directions, they will separate from the vertical member and cause the building to collapse (National treasure: Yeosu Jinnamgwan).

This can be difficult to detect in the early stages. This is because it is not possible to check the separation phenomenon by covering the roof, as shown in Figure 5. The structure of a hanok has limitations in terms of visual judgment because the cross-joint and unidirectional joint are not exposed to the outside. If the unidirectional joint members are constantly moving in different directions, it is important to find the cause during the initial diagnosis because the building is in a dangerous state of collapse.

2.2. Documentation of Hanok Cultural Heritage

Cultural heritage is defined as humanly or naturally formed national, ethnic, or global heritage that has high historical, artistic, scholarly, or scenic value [10].

The head of the Cultural Heritage Administration may designate important tangible cultural properties as treasures after deliberation by the Cultural Heritage Committee. In addition, cultural properties under the category of treasures that are highly valuable and rare from the perspective of human culture may be designated as national treasures after deliberation by the Cultural Heritage Committee [11].

Cultural heritages that are equivalent to treasures or national treasures are preserved and managed as nationally designated cultural heritages. Hanok cultural heritage requires continuous management because the main structural material is wood and damage and deformation occur due to the aging of the structure over the years.

In order to preserve and protect the value of cultural heritage, a fundamental plan for national heritage repair is established every five years after deliberation by the National Heritage Repair Technical Committee in accordance with Article 4(2) of the Act on the Repair of Cultural Properties (National Heritage Repair), and a detailed implementation plan is established and implemented based on it.

While replacing the entire aging structure with new wood can provide a sense of structural stability, the Standard Specifications for Cultural Properties states that cultural heritage repairs should be based on the principle of maintaining the original. The original style, technique, and surrounding environment must also be preserved. Therefore, if there is a risk of collapse or damage, the existing structural materials can be reused. In the case of major structural materials with large cross-sections such as columns and Daedeulbo, it is not easy to find original materials in Korea. Therefore, the reuse rate is relatively high for structural materials with large cross-sections, and only the damaged parts are removed and repaired in the same form as the original (Figures 6 and 7).

Figure 6. Damage to the lower part of a column. The lower part of the column was damaged by termites. (National treasure: Yeosu Jinnamgwan.).

Figure 7. Repairing the lower part of a column. According to the principle of preserving the original, the whole column is not replaced, but only the damaged part is cut out, and a new one of the same shape is made. This is a common method for repairing a hanok. (National treasure: Yeosu Jinnamgwan.).

The documentation of Korea's cultural heritage began in 1958 with the publication of the Repair Report of the Geungnakjeon Hall of Muwisa Temple, and in earnest, in 1999, with the publication of the Precision Measurement Report on Important Wooden Cultural Properties series [12].

The methods for recording are divided into two main categories: surveying while maintaining the original state and surveying while dismantling the building. Dismantling is carried out when repairing structural cultural heritage problems, which allows for the precise observation and recording of the joint techniques of hanoks. The actual measurement and repair report is highly reliable as it records the details of the foundation, structure, materials, techniques, and photographs of the hanok.

2.3. Measuring Column Movement in a Hanok

The leaning of columns, the main structural members that support a building, is a very dangerous phenomenon. In some cases, the change in column leaning is so slight that it is difficult to recognize, and in other cases, the change is so severe that it has a serious structural impact on the building [12].

In hanoks, column inclination is artificially reflected to some extent. In order to give the hanok a sense of visual and structural safety, the columns are inclined inward using a technique called Anssolim. When erecting a column, the upper part of the column is inclined slightly toward the inside of the building. This is interpreted as a safety measure against the loads that roofing materials would displace to the outside of the eaves [2] (Figure 8).

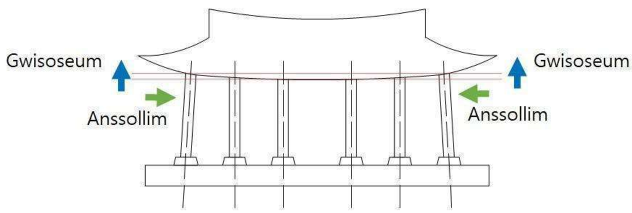

Figure 8. Gwisoseum and Anssollim. To provide structural stability without making the roof appear to be drooping, Anssollim, in which the columns are inclined inward to the center of the plane, and Gwisoseum, in which the columns at the corners of the hanok are slightly higher than the other columns, are used.

In the Song Dynasty of China's Ying Zao Fa Shi, an Anssolim was called a side angle. A side angle was defined as the proportional slope for a column length of 1 Ja, with the different inclination of the front columns sloped by 1 Pun for 1 Ja and the side columns sloped by 0.8 Pun for 1 Ja [13].

In the documentation of the cultural heritage survey and repair report, measurements were taken to estimate the presence or absence of the Anssolim and Gwisoseum. The locations of the measurements were recorded on the x and y axes, comparing the movement of the lower and upper centers of the columns (Figure 9).

The difficulty with investigating Anssollim is that the nature of wooden structures is such that deformation is inevitable, making it difficult to accurately determine the original intent after a significant period of time has passed. Even if the degree of leaning is numerically confirmed, it is not possible to know the degree of inclination at the time of the original plan, and the degree of deformation is not easy to identify [14] (Figure 9).

Cultural heritages with more than one report issued for a single building are divided into two time periods: before and after the commercialization of computers in the 2000s. In order to utilize comparable data to identify changes in column movement, it is necessary to have high precision and a low amount of missing information. Therefore, column-leaning data were extracted from survey and repair reports published after the 2000s and used in this study.

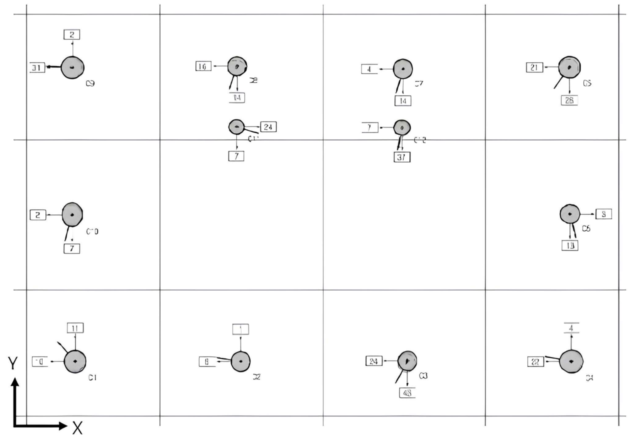

Figure 9. Measurement of column movement. This is a floor plan showing the movement of a column in a hanok. The circle is the cross-section of the column, the arrow is the direction of movement, and the number in the square is the measurement of the distance the column moved (treasure: Bogyeongsa Jeokgwangjeon) [14].

3. Methodology

3.1. Research Flowchart

The research methodology was conducted in three steps, as shown in Figure 10.

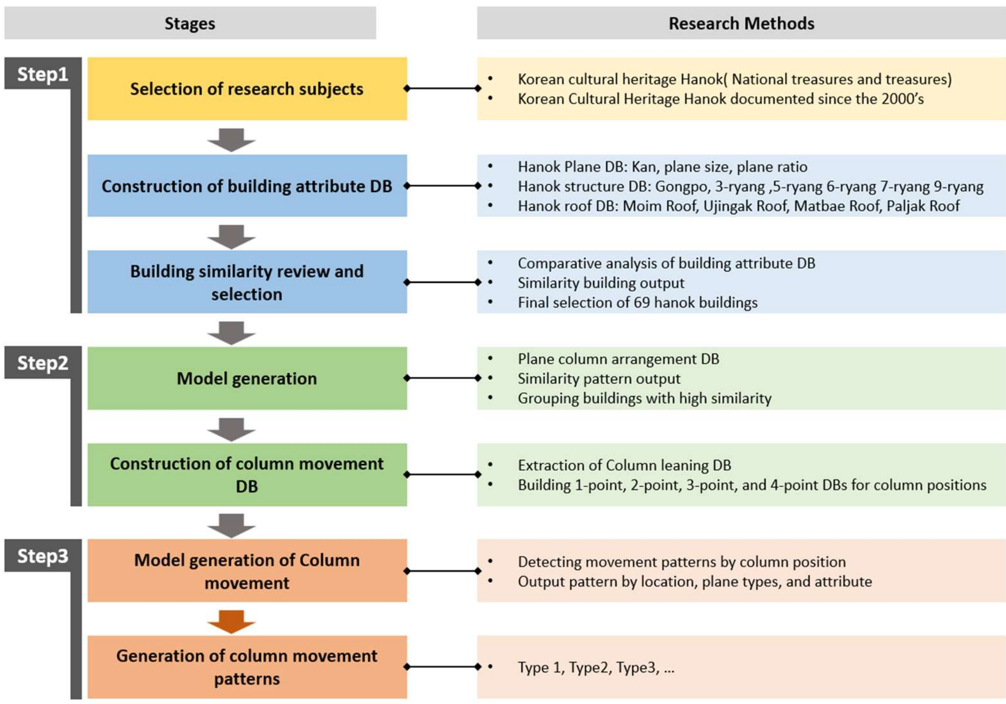

Figure 10. Research flowchart.

In the first stage, buildings from the 2000s or later that are well-documented as Korean cultural heritage hanoks were selected. The hanoks have a variety of functional, site, and environmental elements. Therefore, a building attribute database was constructed. The building attribute DB mainly consists of the floor plan, structure, and roof, where the floor plan is represented by the values of kan, plane size, and plane ratio, and the hanok structure is represented by the values of 3-, 5-, 6-, 7-, and 9-ryang, which represent the type of Gongpo and the scale of the building. Roof type, which represents the overall shape of the hanok, was also applied. Based on these attribute DBs, 69 buildings were selected as the result of the building similarity check.

In step 2, for each of the 69 hanok buildings selected in the first step, a front, back, side, and corner column arrangement DBs were built according to the floor plan and column location. Based on the column arrangement database, a grouping of buildings with high similarity was carried out by synthesizing plan modules, column locations, and scale, and optimized models were generated. Then, the leaning value of each column was entered, and the location where the movement of the column needed to be observed was specified by reflecting the structural characteristics of the hanok. The column location point groups were classified into 1-point, 2-point, 3-point, and 4-point formats. One point was used to analyze the movement of all single columns, while two points were used to analyze the movement of columns in a structure where two columns were directly connected to a horizontal member as a group. Three points were used to analyze the movement of three columns in a group, which are the location of a corner in a planar structure. Four points were grouped to analyze the movement of four columns, which is a step to output the overall movement of the building.

Step 3 was used to derive movement patterns for 1, 2, 3, and 4 columns grouped according to the location of the columns. The final step was used to derive column movement patterns by type by comparing and analyzing the floor plan, structure, and roof attributes.

3.2. Selecting a Study Subject

Korea's nationally designated cultural heritage is categorized into seven types: national treasures, treasures, historic sites, scenic spots, natural monuments, national intangible cultural properties, and national folk cultural properties. The total number of national treasures and treasures in dry construction cultural heritage is 834, including 578 stone cultural heritages (73 national treasures and 505 treasures) and 256 wooden cultural heritages (25 national treasures and 231 treasures) (as of 31 December 2022) [15].

Wooden cultural heritages are buildings whose main structure is made of wood. These include hanoks that are the subject of this study.

Korean cultural heritage is documented for preservation and management. Since drawings of old architecture do not exist, digital drawings were created by directly measuring the existing architecture. In addition, when repairs are made to address defects in hanok architecture, a survey and repair report is mandatory, which contains the details of the repairs and detailed drawings. These reports are reviewed and released by the Korea Cultural Heritage Administration and are highly reliable. In particular, the report contains a record of measuring the movement of the columns, and the direction and distance of the movement in the lower center of the column and the upper center of the column are shown, so the data were collected based on the report.

There are 256 hanoks designated as cultural heritage in Korea, but the biggest factor in their designation as cultural heritage is their rarity. Since there are specialized architectural forms, it was important to select representative architectures with a common hanok structure type.

The selection criteria for this study were the floor plan, section, and roof in the order, and representative models of hanoks were selected. In terms of the floor plan, there are "ㅡ" shapes, "ㄱ" shapes, "ㄷ" shapes, and "ㅁ" shapes, where the "ㅡ" shape is the most basic hanok floor module, and other forms are created by developing from it. Since the main goal of this study is to compare as many similar buildings as possible to identify common causes, the "ㅡ"-type buildings with the largest number of samples were selected.

The floor plan of a hanok is characterized by expandable modules that increase by 1 kan in either the x-axis or y-axis direction. The buildings under study also include buildings with up to 15 kan in the x-axis direction. Expansion on the y axis is specialized and found in large-scale buildings such as palaces, as it requires large horizontal member lengths and cross-sections (Figure 11). Therefore, the floor modules are related to the cross-sectional structure.

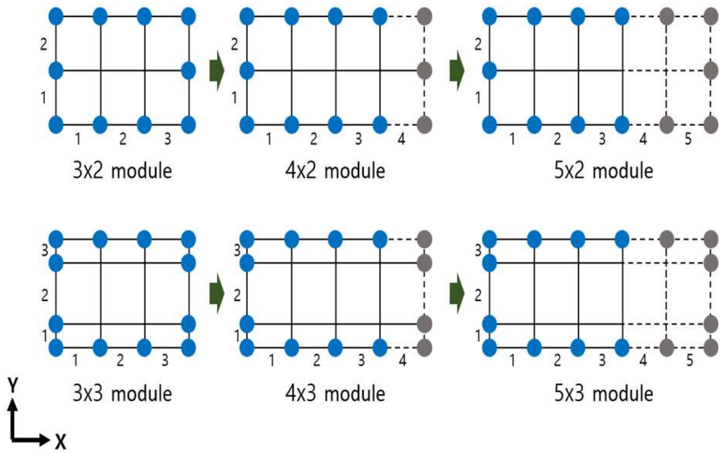

Figure 11. Expansion of hanok floor modules.

There are five-, six-, seven-, and nine-ryang structures, with the nine-ryang structure being the longest and rarest structural form in the y-axis direction of the plane. Typical hanok structures are 5- and 7-ryang and include 96% of the buildings studied. Types of representative hanok roofs are Moim, Ujingak, Paljak, and Matbae, and they are all included in the studied buildings.

In the end, after eliminating buildings for which the column movement data in the documentation report were difficult to verify and identifying buildings with high similarity based on floor plans, sections, and roof features, 69 buildings were finally selected (Table 1).

Table 1. List of hanoks studied.

NO	Cultural Heritage Name	NO	Cultural Heritage Name
1	Gangjin muwisa geungnakbojeon	36	Yeongcheonhyanggyo daeseongjeon
2	Yeongcheon eunhaesa geojoam yeongsanjeon	37	Cheongju ansimsa daeungjeon
3	Andong bongjeongsa geungnakjeon	38	Uljin buryeongsa eungjinjeon
4	Yeongju buseoksa muryangsujeon	39	Yeongcheon eunhaesa baekeungam geungnakjeon
5	Yesan sudeoksa daeungjeon	40	Gongju magoksa daegwangbojeon
6	Hapcheon haeinsa janggyeongpanjeon	41	Gochang seonunsa chamdangam daeungjeon
7	Suncheon songgwangsa guksajeon	42	Suncheon jeonghyesa daeungjeon
8	Andong bongjeongsa daeungjeon	43	Anseong cheongnyongsa daeungjeon
9	Wanju hwaamsa geungnakjeon	44	Iksan sungnimsa bogwangjeon
10	Seoul seonggyungwan daeseongjeon	45	Gimje geumsansa daejangjeon
11	Seosan gaesimsa daeungjeon	46	Cheongdo daebisa daeungjeon
12	Yecheon yongmunsa daejangjeon	47	Cheongdo unmunsa daeungbojeon
13	Ganghwa jeongsusa beopdang	48	Cheongdo daejeoksa geungnakjeon
14	Cheongyang janggoksa sangdaeungjeon	49	Boeun beopjusa wontongbojeon
15	Ganghwa jeondeungsa daeungjeon	50	Haenam mihwangsa daeungjeon
16	Ganghwa jeondeungsa yaksajeon	51	Yangsan sinheungsa daegwangjeon
17	Cheongyang janggoksa hadaeungjeon	52	Haenam mihwangsa eungjindang
18	Changnyeong gwallyongsa daeungjeon	53	Uljin buryeongsa daeungbojeon
19	Gochang seonunsa daeungjeon	54	Wanju songgwangsa daeungjeon
20	Buan naesosa daeungbojeon	55	Goheung neunggasa daeungjeon
21	Buan gaeamsa daeungjeon	56	Naju bulhoesa daeungjeon
22	Gurye hwaeomsa daeungjeon	57	Suncheon seonamsa daeungjeon
23	Suncheon songgwangsa yeongsanjeon	58	Nonsan donamseowon eungdodang
24	Jeju gwandeokjeong	59	Cheongsong daejeonsa bogwangjeon
25	Sancheong yulgoksa daeungjeon	60	Seongjuhyanggyo daeseongjeon
26	Najuhyanggyo daeseongjeon	61	Seongjuhyanggyo myeongnyundang

Table 1. *Cont.*

NO	Cultural Heritage Name	NO	Cultural Heritage Name
27	Yeosu heungguksa daeungjeon	62	Gimcheon jikjisa daeungjeon
28	Hongseong gosansa daeungjeon	63	Gyeongbokgung sajeongjeon
29	Nonsan ssanggyesa daeungjeon	64	Gijang jangansa daeungjeon
30	Busan beomeosa daeungjeon	65	Haenam daeheungsa cheonbuljeon
31	Andong bongjeongsa hwaeomgangdang	66	Yangsan tongdosa yeongsanjeon
32	Andong bongjeongsa gogeumdang	67	Yangsan tongdosa daegwangmyeongjeon
33	Hadong ssanggyesa daeungjeon	68	Uiseong daegoksa daeungjeon
34	Dalseong taegojeong	69	Pohang bogyeongsa jeokgwangjeon
35	Wanju wibongsa Bogwangmyeongjeon		

3.3. Building a DB in a Hanok

3.3.1. Floor Plan DB for Hanok

A hanok is composed of vertical and horizontal members that are joined to each other to form a space. The spatial area of a hanok uses the unit of "kan", and in the elevation, the space between a column and another column is 1 "kan", and the space consisting of one column on the x axis and one column on the y axis is also 1 "kan". The scale of Figure 12 is three columns in the front and three columns on the side, and the building size can be estimated using kan, even if the distance between columns is different.

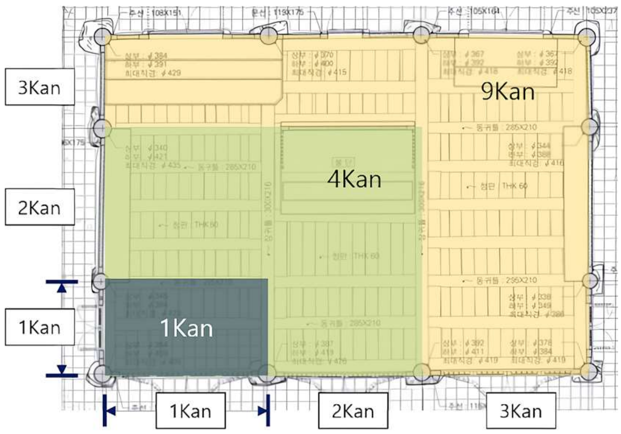

Figure 12. A 3 × 3 (9-kan) floor plan [16]. In the elevation of a hanok, a unit of 1 kan is used between columns. Additionally, 1 kan also means a unit of space. Therefore, this floor plan is 3 kan in the front and 3 kan on the side, or 9 kan in size.

On a similar scale, 3 × 2 and 3 × 3 buildings account for 64% (Table 2), and in the case of Figure 13, the 3 × 3 plane is expanded by 2 kan in the x-axis direction. As such, hanok buildings can be extended by adding columns along the x axis to expand the space configuration. The buildings under study also include buildings with up to 15 kan.

Table 2. Floor plan scale.

Size	3 × 2	3 × 3	3 × 4	4 × 2	4 × 3	5 × 3	5 × 4	7 × 3	15 × 2	Total
The number of buildings	15	29	4	1	1	14	3	1	1	69
Percentage	22%	42%	6%	1%	1%	20%	4%	1%	1%	100%

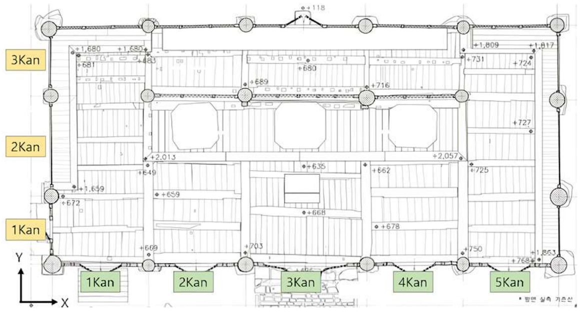

Figure 13. A 5 × 3 (15-kan) floor plan [17]. This floor plan has 5 kan in the front and 3 kan on the side. In Figure 12, the front is increased by 2 kan.

The movement of the column was predicted to vary depending on the ratio of the floor plan, so it was measured as the ratio of the horizontal length and the vertical length of the floor plan. The closer the ratio is to 1, the more square the building is. The buildings in this study generally had a ratio of 0.6 to 0.7 with the highest proportions and were generally close to square (Table 3). The horizontal length of the buildings ranged from 5667 mm to 60,536 mm, and the vertical length ranged from 3793 mm to 12,919 mm.

Table 3. Floor plan ratio.

Floor Plan Ratio	0.1	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Total
The number of buildings	1	1	2	9	18	24	9	5	69
Percentage	1.4%	1.4%	2.9%	13.1%	26.1%	34.8%	13.1%	7.2%	100%

Figures 12 and 13 are on the smaller side of the scale, as the horizontal and vertical ratio of the plane is closer to 1:1. Therefore, the data values for the ratio of the floor plan and kan according to the arrangement of the columns were extracted.

3.3.2. Hanok Structure DB

The x-axis direction of the hanok building has a scale of 15 kan, as shown in Table 2, while the number of kan on the y axis is confirmed to be 2 to 4 kan. This means that, in the y-axis direction of the hanok, the Daedlebo, the horizontal member with the second largest cross-section after the column, is joined to the columns. The scale of the sides is determined using Dori. Three- to five-ryang buildings are common in civilian houses, while seven- to nine-ryang buildings are found in palaces and temples.

In general, the structure of a Dori is determined by an odd number, which makes the section symmetrical, as shown in Figures 14–16, but in some unusual cases, the structure is asymmetrical, as shown in Figure 17.

The studied buildings are distributed in the order of 5-ryang buildings (71%) with 49 cases, 7-ryang buildings with 17 (25%) cases, 9-ryang buildings with 2 (3%) cases, and 6-ryang buildings with 1 (1%) case (Table 4).

Table 4. The structure of hanoks.

Structure	5-Ryang	6-Ryang	7-Ryang	9-Ryang	Total
The number of buildings	49	1	17	2	69
Percentage	71%	1%	25%	3%	100%

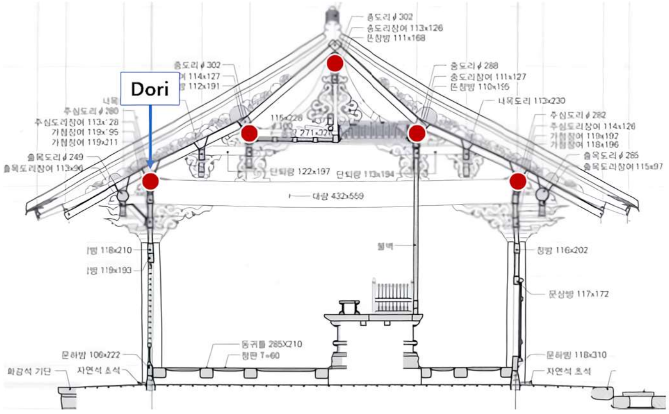

Figure 14. The number of Dori: A 5-ryang structure [16]. In this cross-sectional architectural drawing, the red circles represent Dori, which are named 5, 6, 7, 8, or 9 depending on the number of Dori. A higher number indicates a large structure with a lot of space (Figures 15–17).

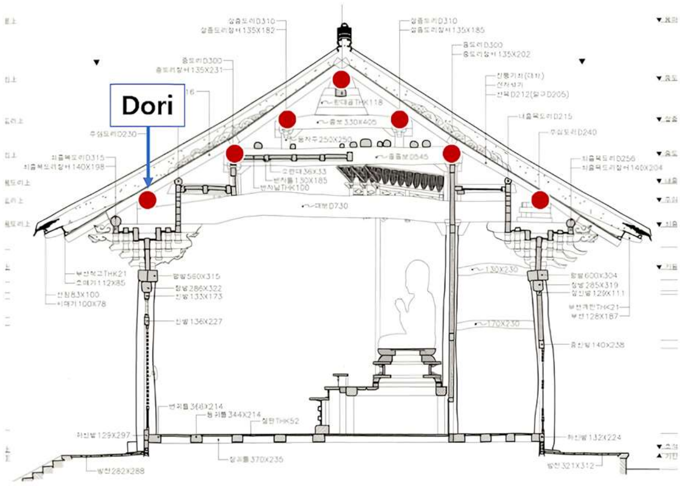

Figure 15. The number of Dori: a 7-ryang structure [18].

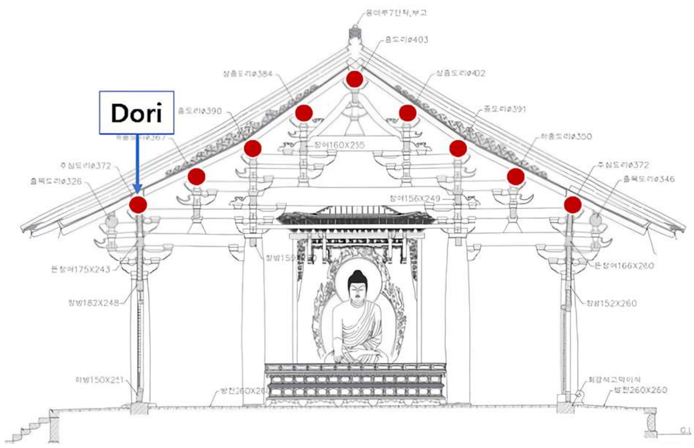

Figure 16. The number of Dori: a 9-ryang structure [19].

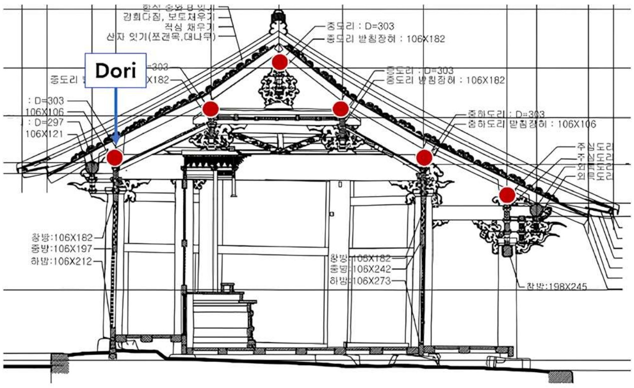

Figure 17. The number of Dori: a 6-ryang structure [20].

A Gongpo transfers the weight of the roof to the columns and makes the building's elevation magnificent. The style of a Gongpo varies by era and region, and the structure and construction methods vary, but the styles are categorized as Ikgong, Jusimpo, Dapo, Haangpo, and Mindori.

Choikgong is a simple form (Figure 18), while Jusimpo and Dapo are made up of several smaller members to form a single Gongpo. In the Choikgong and Jusimpo styles, a Gongpo is placed only on the column (Figures 18 and 19), and in the Dapo style, a Gongpo is placed even between the columns (Figure 20). The styles of Gongpo studied are Choikgong, Jusimpo, and Dapo, with Dapo being the most common with 51 cases (74%), followed by Jusimpo with 14 (20%) cases, and Choikgong with 4 (6%) cases (Table 5).

Figure 18. The style of Gongpo: Choikgong [21]. Choikgong (white circle) has a simple form and is placed on a column. It is often found in civilian architecture.

Figure 19. The style of Gongpo: Jusimpo [22]. A Jusimpo (white circle) is more ornate than a Choikgong and is placed on a column.

Figure 20. The style of Gongp: Dapo. The Dapo style (white circle) is the most splendid. In the same form as Jusimpo, a Gongpo is added to the top of a horizontal member between columns. It is mainly found in palace and temple buildings.

Table 5. Gongpo of a hanok.

Structure	Choikgong	Jusimpo	Dapo	Total
Number of buildings	4	14	51	69
Percentage	6%	20%	74%	100

3.3.3. Hanok Roof DB

The roof is the most proportional part of a hanok's elevation. Depending on the form of the roof, the appearance of the building changes, and the structure is also different. The styles of roofs are broadly categorized as Moim, Ujingak, Paljak, and Matbae. The Moim style is formed by gathering in the center of the plane, as shown in Figure 21, which can be seen on a plane that is close to a square. If the Moim roof becomes a long horizontal plane, a Ujingak roof such as that in Figure 22 is formed.

Figure 21. The Moim roof style [23].

A Matbae roof is a form in which the front and back sides are symmetrically sloped, and the left and right sides are vertically lowered, as shown in Figure 23. A Paljak roof is a structure formed by mixing a Ujingak roof and Matbae roof, and it features one of the most beautiful curves in hanok architecture (Figure 24).

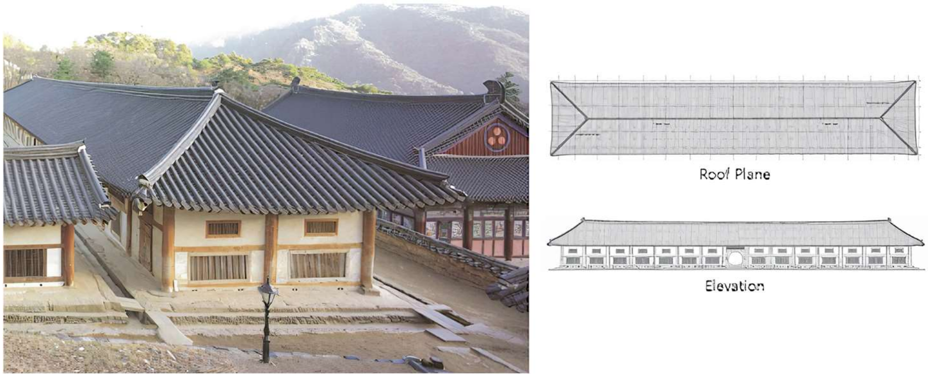

Figure 22. The Ujingak roof style [24].

Figure 23. The Matbae roof style [25].

Figure 24. The Paljak roof style [26].

The surveyed buildings are dominated by Matbae roofs and Paljak roofs, with the lowest proportion of roofs being in the Moim and Ujingak styles (Table 6).

Table 6. Hanok roof.

Structure	Moim Roof	Ujingak Roof	Matbae Roof	Paljak Roof	Total
The number of buildings	1	1	29	38	69
Percentage	1.4%	1.4%	42.1%	55.1%	100

The movement of the building is most affected by the load on the roof, and in the case of a Paljak roof, a member called a Chuyeo is placed in the corner to lengthen the eaves. Therefore, the roof data values were included to observe the movement of the columns according to the size of the roof.

3.3.4. Column Movement in Hanok DB

The movement of a column can be a primary cause, or it can be a secondary or tertiary cause affected by other factors. Therefore, a comparative analysis of the movement of similar buildings can provide clues to predict required repair methods or structural defects.

The main data are the *x*-axis and *y*-axis movement distances extracted based on the upper center of the exterior columns (Figures 25 and 26). As a result of extracting the movement data for each column, the movement values ranging from 1 mm (no movement) to 363 mm were confirmed. When checking the movement of the columns by direction on the plane, the maximum movement distance of the front column was 269 mm, and the average was 55 mm; the maximum movement distance of the back column was 349, mm and the average was 60 mm; the maximum movement distance of the left column was 275 mm, and the average was 48 mm; and the maximum movement distance of the right column was 363 mm, and the average was 50 mm (Table 7).

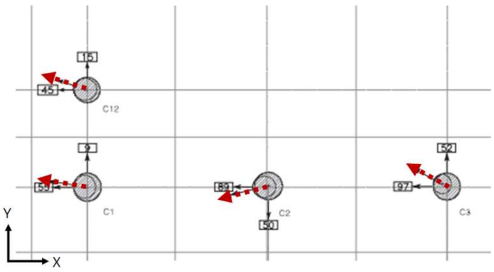

Figure 25. Measurement of column leaning [27]. This floor plan shows the columns' movement. The larger circles represent the lower part of a column, while the smaller circles represent the upper part of a column. The numbers in the rectangular boxes are the values that move along the *x* and *y* axes. The arrows indicate the movement direction of the upper part of a column. In particular, the red arrows indicate the average direction.

More important than the distance of the columns is the direction of their movement. A hanok is constructed by joining horizontal members among columns. The joints of the horizontal and vertical members were joined by carving the members to a depth of 1/2 each. Changbang and Pyeongbang, which are directly joined to the upper part of the columns, are relatively stable because the columns have a large cross-sectional area. However, the Gongpo are made up of smaller members. The member called Salmi in the Gongpo has a cross-sectional length of 110 mm. The depth of the horizontal member at the joint section is 55 mm. The horizontal movement of the columns in different directions could have resulted in a structural hazard. As shown in Figure 27, the upper and lower parts are not integrally connected with reference to the A standard. It is also possible that the movement of the column and the movement of the Gongpo members are different from each other.

A	AM	AN	AO	AP	AQ	AR	AT	AU	AV	AW	AX	AY	BA	BB	BC	BD	BE	BF
cultural heritage Name	Front X-Axis leaning	Front Y-Axis leaning	Angle 23~68 113~158	Front leaning direction	Minimum value	Maximum value	Back X-Axis leaning	Back Y-Axis leaning	Angle 23~68 113~158	Back leaning direction	Minimum value	Maximum value	Left X-Axis leaning	Left Y-Axis leaning	Angle 23~68 113~158	Left leaning direction	Minimum value	Maximum value
Gangjin muwisa geungnakbojeon	43	-23	-28°	↘	13	65	41	2	2°	→	1	60	23	1	3°	→	13	44
Yeongcheon eunhaesa geojoam yeongsanjeon	3	20	81°	↑	0	24	-11	9	141°	↖	0	42	-20	52	111°	↑	10	30
Andong bongjeongsa geungnakjeon	-2	-5	-113°	↙	2	14	-3	-2	-145°	↙	5	11	3	1	27°	↗	5	27
Yeongju buseoksa muryangsujeon	-22	-8	-161°	←	1	44	-2	-42	-92°	↓	2	16	17	-19	-48°	↘	1	34
Yesan sudeoksa daeungjeon	-13	36	110°	↑	8	80	11	-43	-76°	↓	9	59	41	-2	-3°	→	25	59
Hapcheon haeinsa janggyeongpanjeon	18	0	-1°	→	6	67	-4	29	97°	↑	2	31	-43	44	134°	↖	4	67
Suncheon songgwangsa guksajeon	-31	-27	-139°	↙	23	52	-2	-43	-93°	↓	1	20	-17	-15	-138°	↙	11	23
Andong bongjeongsa daeungjeon	-62	3	177°	←	5	136	-116	-51	-156°	↙	61	170	-47	-31	-147°	↙	13	90
Wanju hwaamsa geungnakjeon	15	62	76°	↑	9	32	-12	-35	-109°	↓	10	49	27	30	49°	↗	13	79
Seoul seonggyungwan daeseongjeon	4	49	85°	↑	1	20	25	-42	-59°	↘	1	50	23	-2	-5°	→	4	43
Seosan gaesimsa daeungjeon	-11	16	124°	↖	5	16	13	-11	-41°	↘	8	28	11	0	-1°	→	5	26
Yecheon yongmunsa daejangjeon	-11	9	139°	↖	4	15	-13	48	105°	↑	7	18	-9	33	105°	↑	0	15
Ganghwa jeongsusa beopdang	51	-6	-6°	→	45	62	76	-66	-41°	↘	66	90	75	-11	-9°	→	62	99
Cheongyang janggoksa sangdaeungjeon	23	-17	-37°	↘	5	37	-28	3	175°	←	12	52	-11	-41	-106°	↓	11	52
Ganghwa jeondeungsa daeungjeon	-2	30	93°	↑	1	37	-12	-59	-102°	↓	2	59	25	-16	-33°	↘	14	38
Ganghwa jeondeungsa yaksajeon	17	-3	-11°	→	4	40	28	-81	-71°	↓	11	71	67	-29	-24°	↘	40	91
Cheongyang janggoksa hadaeungjeon	6	36	81°	↑	10	35	10	-14	-56°	↘	13	34	30	6	11°	→	22	34
Changnyeong gwallyongsa daeungjeon	0	12	89°	↑	11	50	-25	-25	-135°	↙	12	35	14	-21	-57°	↘	5	50
Gochang seonunsa daeungjeon	-71	67	137°	↖	51	105	-30	-11	-160°	←	31	115	-61	30	154°	↖	58	136

Figure 26. The x-axis and y-axis movement data of the upper part of the column. The column movement data are the values of the front, back, left, and right columns for the x-axis and y-axis movement distances of the columns per study subject. The arrows indicate the direction of column movement.

Table 7. Movement distance of columns.

Classification	Front			Back			Left			Right		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
Movement distance (mm)	1	269	55	1	349	60	1	275	48	1	363	50

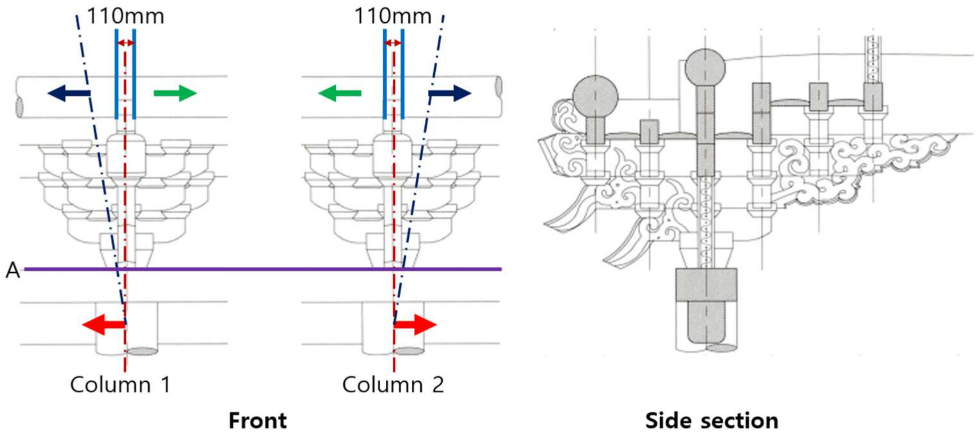

Figure 27. Predicted movement of columns. These show the front and side views of Gongpo. In "the front", if the two columns have different directions of movement, the uppermost horizontal members undergo separation from each other. These horizontal members overlap the vertical members by 55 mm. If the separation distance is higher than this, collapse will occur.

The movement of a building was extracted by averaging the total numerical values of the columns (Table 8). The column line in the front was the most common with 19 (27.5%) buildings leaning in the back direction, while the column line in the back had 18 (26.1%) buildings leaning in the front direction, the column line on the left side had 14 (20.3%) buildings leaning in the right direction, and the column line on the right side had 18 (26.1%) buildings leaning in the left direction.

Table 8. Movement direction of hanoks.

The Four Sides of the Column Line	↑	↗	→	↘	↓	↙	←	↖
Front	**19 (27.5%)**	7 (10.1%)	11 (15.9%)	8 (11.6%)	2 (2.9%)	9 (13%)	4 (5.8%)	9 (13%)
Back	7 (10.1%)	2 (2.9%)	8 (21.7%)	15 (21.7%)	**18 (26.1%)**	11 (15.9%)	4 (5.8%)	4 (5.8%)
Left side	7 (10.1%)	11 (15.9%)	**14 (20.3%)**	13 (18.8%)	7 (10.1%)	8 (11.6%)	5 (7.2%)	4 (5.8%)
Right side	7 (10.1%)	8 (11.6%)	7 (10.1%)	7 (10.1%)	5 (7.2%)	7 (10.1%)	**18 (26.1%)**	10 (14.5%)

These numerical representations have limitations in representing columns and column movements in the way utilized in the actual repair reports (Table 8). Therefore, the experiment was conducted in stages by combining single columns, two columns, three columns, and four columns.

3.4. Simulating Column Movement Based on UMAP and DBSCAN

Figure 28 shows the column movement simulation process, and the technology used to implement it was Python 3.9.13, Python 3.9 standard library, and Scikit-learn 1.3.1 [28].

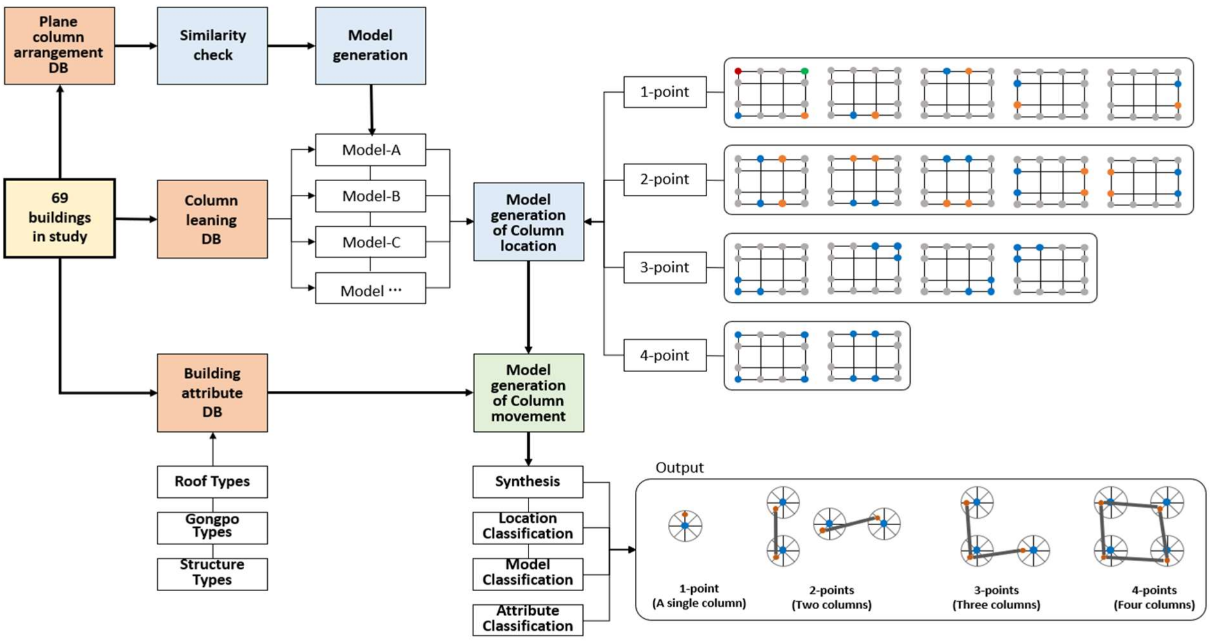

Figure 28. Column movement model generation process.

After inputting the DB value of the floor plan column arrangement for the 69 selected buildings, the model was generated using a similarity check. If the types were completely different, model A, model B, and model C were created, and if they were derived, models A-1, A-2, etc., were created.

Next, to reflect the structural characteristics of a hanok, a model was created and analyzed using a 1-point to 4-point method according to the number of columns or connections with horizontal members. The one-point movement analysis is a format for analyzing the movement of each external column that is a single column. The two-point movement analysis is a format for analyzing the movement of the front and back columns in a structure where the horizontal member is joined to the columns. A three-point movement analysis is a format for analyzing the movement of three columns at the corners of a building. Four-point movement analysis is classified as a format that connects four columns at each corner to analyze the movement of the entire shape of the building and a model that analyzes the movement of four columns consisting of two horizontal members in the center of the building.

To cluster the data, the column arrangement DB, column movement DB, and building attribute DB were optimized. In terms of column movement, which is the most important movement in this study, the direction and movement values vary, so it was optimized with a total of nine types of column movement directions, in addition to the case of no column movement (Figure 29).

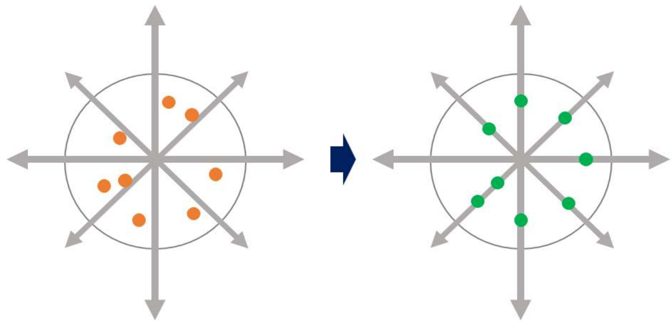

Figure 29. Optimizing the movement direction of the upper part of columns. The circle represents the lower part of a column, and the orange and green dots are the movement distances of the upper part of the column. The arrows indicate the direction of movement in the upper part of the column. As shown with the orange dots, the numerical values varied, so the types with the most similar direction and distance values were optimized with the green dots.

The results of clustering the pre-processing data based on the column arrangement DB, column movement DB, and building attribute DB were derived in a three-dimensional format. In this case, the number of samples increased exponentially, resulting in the curse of dimensionality, which degrades the performance of clustering. The UMAP [29] algorithm was used to optimize and cluster the data in two dimensions using the features of each element.

UMAP, T-SNE, and PCA are the three main dimension reduction algorithm techniques. T-SNE requires a long dimension reduction process and has a high probability of data distortion when reducing low dimensions, and PCA has the disadvantage of mishmashing clustered data. UMAP was used because it is faster than the T-SNE and PCA dimension reduction algorithms and preserves essential features better.

DBSCAN [30] and K-MEANS are the main clustering methods for optimized data, but K-MEANS requires the grouping unit to be specified and divides the data into lines even if they are clustered, so there is a high probability of different groups. DBSCAN was used because it does not define the number of clusters but calculates the density of the data for clustering, which is suitable for this study. Therefore, the data optimized with UMAP were clustered using the DBSCAN algorithm. The clustered groups were model A, model B, and model C, and the condition values were eps = 0.5 and min_samples = 1. Finally, the clustered models were analyzed by deriving column movement patterns with similarity (Figure 30).

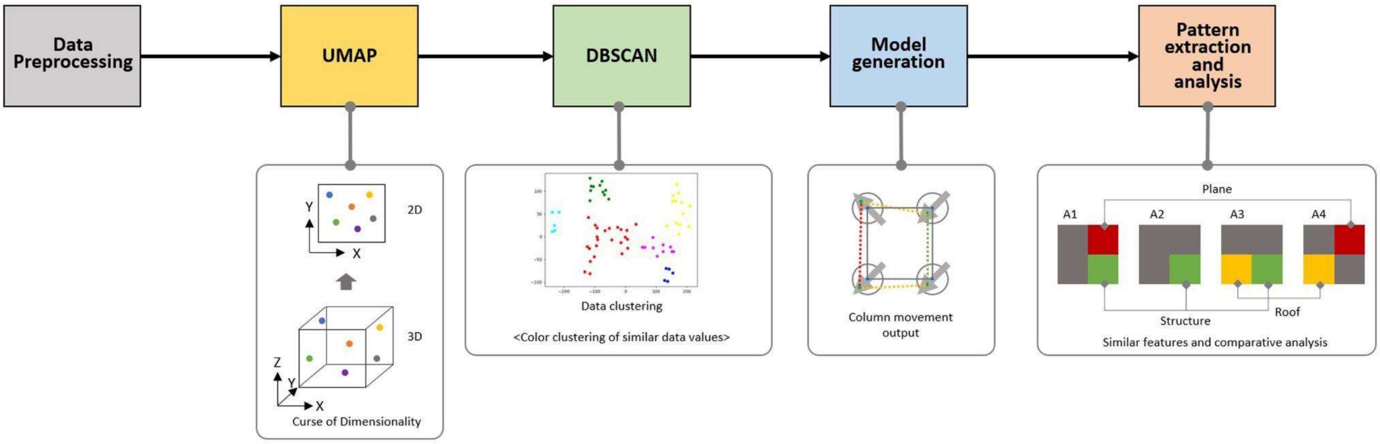

Figure 30. Data clustering and output.

4. Analysis and Synthesis

4.1. Analyzing One-Point Column Movement

4.1.1. Corner Columns

In a hanok, the columns at the corners are called corner columns, and the movement of the four corner columns at each corner was derived for each model. The areas where the columns have no movement or are Anssollim inclined inward to give a sense of stability to the building are marked in gray, and if the frequency of the movement direction is more than 10%, it is marked in yellow. In Figure 31, each of the four corner columns is classified as having one of nine different directions of column movement. Figure 32 indicates that all column movements are synthesized into the same shape by rotating the viewpoint. The proportion of stable corner columns was found to be 27%, while that of unstable columns was found to be as high as 73%.

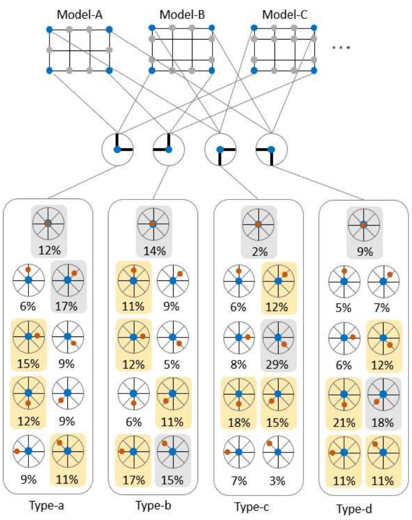

Figure 31. One-point column movement (corner). This shows the movement of the corner columns. In Type-a through Type-d, the blue dots represent the lower center of the column, and the red dots represent the direction in which the upper center of the column moves. The gray background shows the column movement corresponding to no movement and an inclination (Anssollim). The yellow color indicates a high frequency of the movement direction.

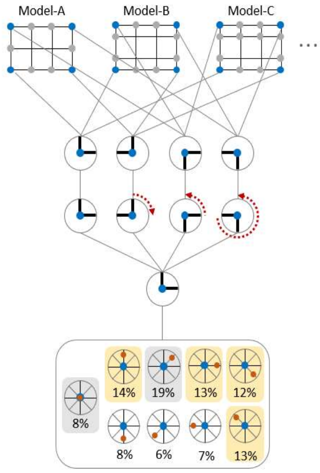

Figure 32. One-point column movement synthesis (corner). In Figure 31, the movements are synthesized for each corner column. When looking at the front of the building, there are four different shapes of horizontal members that join to a corner column. When the viewpoint is rotated (red arrow), the four corner columns end up in the same "ㄴ" shape. This is to show the general direction of movement of the corner columns.

4.1.2. The Front Average Column and the Back Average Column

The columns in between the corner columns of a hanok are called average columns. As a result of deriving the movement of the front and back average columns in Figure 33, the proportion of unstable columns in the front columns is high (79%), and the movement direction of the columns is also varied. On the other hand, the unstable columns on the back are lower than the front, at 60%. It can be said that the unstable columns on the back are generally leaning inward, showing a relatively more stable state of movement than the front. Figure 34 indicates that all column movements are synthesized into the same shape by rotating the viewpoint. The overall result shows that 31% of the columns are stable and 69% are unstable.

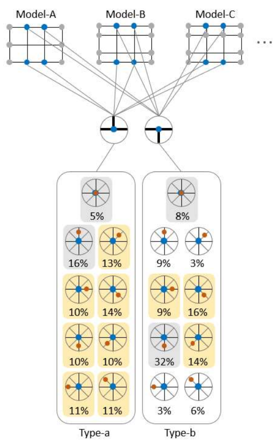

Figure 33. One-point column movement (front/back). This shows the movement of the front and back columns of a hanok. The blue dots show the movement in the lower center of the column and the red dots show the movement in the upper center of the column. The gray color indicates that the columns are not moving or are inclined inward (Anssollim), and the yellow color indicates that the frequency of the movement direction is generally high.

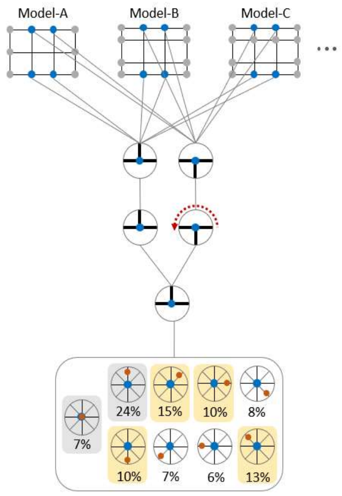

Figure 34. One-point column movement synthesis (front/back). This figure synthesizes the movement of the front and back columns. The horizontal member joined to the front column is shaped as "⊥", and the back is shaped as "⊤". The viewpoint is rotated (red arrow) to synthesize the movement of the columns in the horizontal connection structure method. This is because the connection structure of "⊥" and "⊤" is the same. Thus, the movement of the columns was synthesized in the form of the same "⊥".

4.1.3. The Left Average Column and the Right Average Column

The movements of the left and right columns of the building were derived. In Figure 35, the columns on the left side of the building have a high level of movement toward the inside of the building, while the columns on the right side have a high level of movement toward the outside of the building. If only the left and right columns are considered, the building was observed to move in the "→" direction. Figure 36 indicates that all column movements are synthesized into the same shape by rotating a viewpoint. In total, 30% of the columns were stable and 70% were unstable.

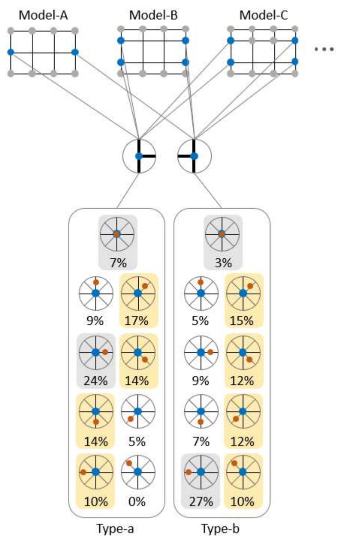

Figure 35. One-point column movement (right/left). This shows the movement of the left and right columns. The blue dots show the movement of the lower center of the column and the red dots show the movement of the upper center of the column.

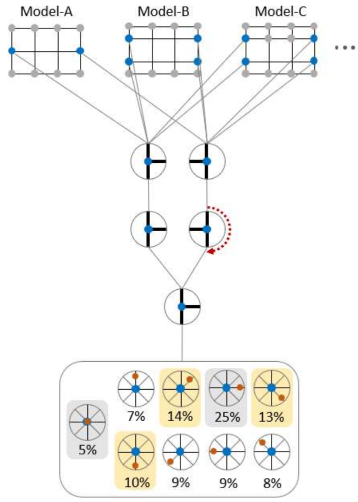

Figure 36. One-point column movement synthesis (right/left). The left column is joined to the horizontal members in a "ㅏ" shape, while the right column is joined to the horizontal members in a "ㅓ" shape. If the viewpoint of the right column is rotated (red arrow), it can be seen that it has the same shape as the left one. This represents the movement of the columns by synthesizing the movement of the columns joined to the horizontal members in the "ㅏ" shape.

4.2. Analyzing Two-Point Column Movement

4.2.1. Daedlebo Direction

A hanok is a post and beam structure that is constructed by connecting columns with beams. The horizontal member that joins the front average column and the back average column is called a Daedeulbo. If the columns have the largest cross-sectional area of the vertical members, the Daedeulbo have the largest cross-sectional area of the horizontal members. The size and length of the cross-sectional area of the Daedeulbo determines the scale of the space. In models A and B, a single Daedeulbo connects column to column, so the width of the space is relatively small. To increase the width of the space, model C connects the beams by placing columns between the columns. The long beam is called the Daedeulbo, and the short beam is called the Toetbo.

The movement of two columns joined to a Daedeulbo was derived, as shown in Figure 37. This is categorized into three types: no movement in the two columns or movement in the same direction, which is set as a stable state; movement of only one column; and movement of two columns in different directions. In total, 41% of the structures were stable, while 59% were unstable. When the results were separated by model, models A and B showed similar column movement, while model C showed two columns moving in different directions, which is a very dangerous condition, at 39% (Figures 38–40).

4.2.2. Dori Direction

The members that join average columns in the position of enclosing the exterior walls of the structure are Changbang, Jangyeo, Pyeongbang, and Dori. Dori is the member that is placed last at the top of the column. Figures 41 and 42 show the movement of two average columns in the front and back, and Figure 43 synthesizes all column movements in the same shape by rotating the viewpoint. The movement of the front columns showed dangerous conditions at 33%, while the movement of the back columns showed dangerous conditions at 46%.

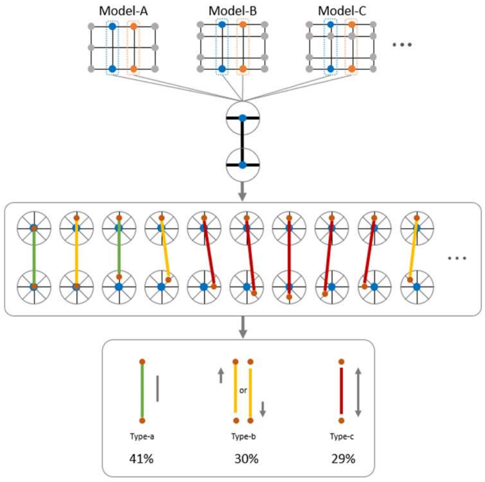

Figure 37. Two-point column movement (Daedeulbo). The front and back columns are joined by a Daedeulbo, which is a horizontal member. The blue dots indicate the lower center of the column, and the red dots indicate the movement in the upper part of the column. The horizontal member joining the front and back columns is represented by green, yellow, and red lines, depending on the joining strength. A green line indicates that the horizontal member is well-joined to the front and back columns. A yellow line indicates that the joint is undergoing separation from one of the front or back columns. A red line indicates that the joints of both the front and back columns are undergoing separation.

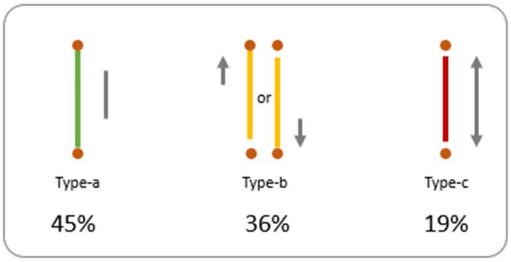

Figure 38. Model A. In floor plan model A, Type-a shows the front and back columns are well-joined to the horizontal member, Type-b shows that one of the front and back columns joined to the horizontal member is undergoing separation, and Type-c shows that both the front and back columns are undergoing separation from the horizontal member.

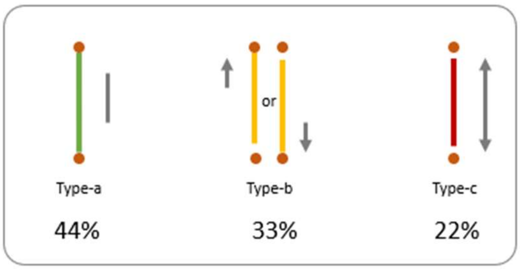

Figure 39. Model B. The type legend is the same as in Figure 38.

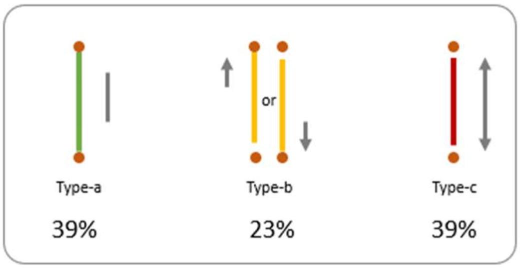

Figure 40. Model C. The type legend is the same as in Figure 38.

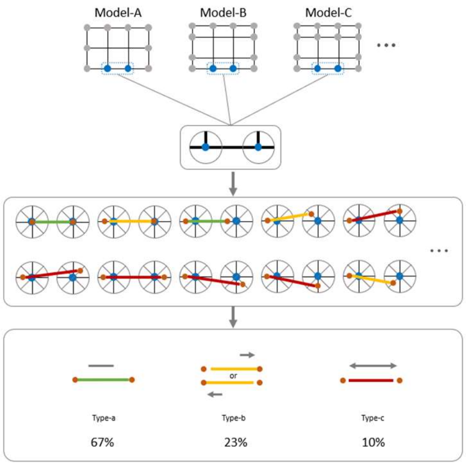

Figure 41. Two-point column movement (front). This shows the movement of two columns on the same line from the front. The blue dots indicate the lower center of the column, and the red dots indicate the movement in the upper center of the column. The horizontal member joining columns are represented by green, yellow, and red lines, depending on the joining strength. A green line indicates that the horizontal member is well joined to both columns, a yellow line indicates that the horizontal member is undergoing separation from one of the two columns, and a red line indicates that the horizontal member is undergoing separation from both columns.

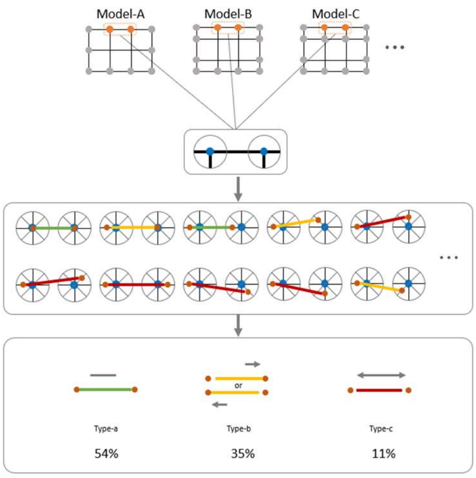

Figure 42. Two-point column movement (back). This shows the movement of two columns on the same line from the back. The color legend is the same as in Figure 41.

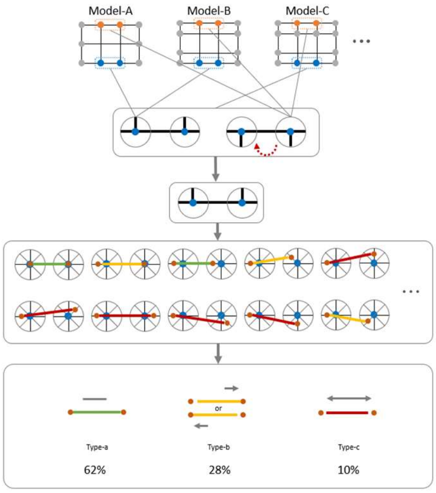

Figure 43. Two-point column movement synthesis (front/back). This shows the synthesized movement of the front columns and the back columns. The horizontal members joining the front columns have a "⊥⊥"-shaped structure, while the horizontal members joining the back columns have a "⊤⊤"-shaped structure. Rotating the viewpoint of the back columns (red arrow) results in the same "⊥⊥"-shaped structure as the front to synthesize the column movement in the same shape. A green line indicates that the horizontal member is well-joined to the two columns, a yellow line indicates that the horizontal member is undergoing separation from one of the two columns, and a red line indicates that the horizontal member is undergoing separation from both columns.

The movement of the columns on the left and right sides was checked. For model A, the average column is joined to the corner columns, so it is excluded. In total, 35% of the columns on the left side were unstable and 37% of the columns on the right side were unstable, which are similar values (Figures 44 and 45). Overall, 65% of the columns were stable and 35% of the columns were unstable, similar to the front column condition (Figure 46).

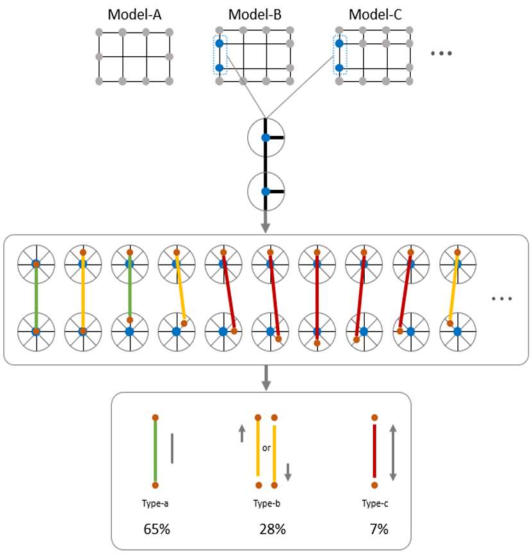

Figure 44. Two-point column movement (left). This shows the movement of the columns on the left line. A green line indicates that the horizontal member is well-joined to the two columns, a yellow line indicates that the horizontal member is undergoing separation from one of the two columns, and a red line indicates that the horizontal member is undergoing separation from both columns.

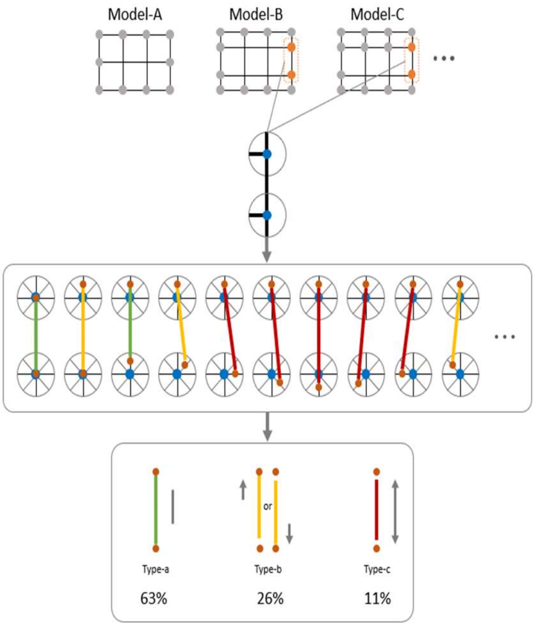

Figure 45. Two-point column movement (right). This shows the movement of the columns on the right line. The color legend is the same as in Figure 44.

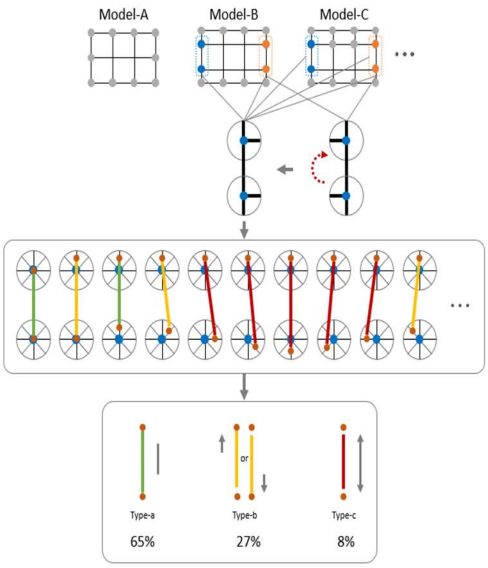

Figure 46. Two-point column movement synthesis (left/right). This is the synthesis of column movements on the left and right lines. The horizontal member joining the left columns has a "ㅏ" shape, and the horizontal member joining the right columns has a "ㅓ" shape. Rotating the viewpoint of the right columns (red arrow) to synthesize the column movements in the same shape results in the same shape "ㅏ" as the left joining structure. The color legend is the same as in Figure 44.

4.3. Analyzing Three-Point Column Movement

Corner Columns

The two horizontal members that are joined to each corner column located at the corners of the hanok are joined by overlapping. Based on this, the joining strength between horizontal members was categorized into nine types. The data values of the locations corresponding to the four corners were extracted, as shown in Figure 47, and the stability of the joining strength between the horizontal members located at the front corner column (Figure 48) and the back corner column (Figure 49) was derived.

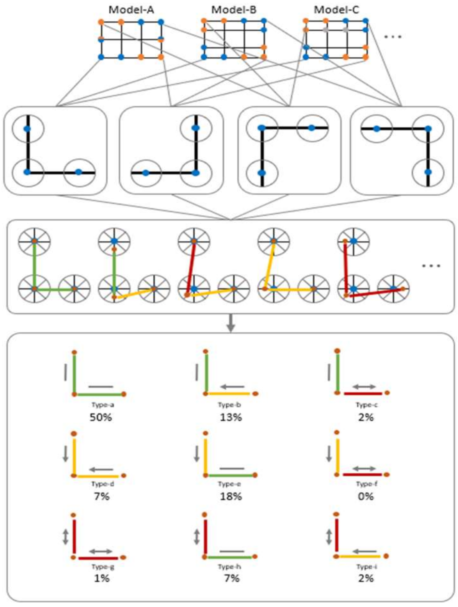

Figure 47. Three-point column movement synthesis. This structure is a total of three columns joined to the horizontal member centered on the corner column. A total of four corner-column parts are synthesized. The corner columns are applied with the Wangchi cross joint shown in Figure 3. It is a stronger connection than the unidirectional joint technique, so three-point movement analysis is used to check the joining strength of the horizontal member when one corner column moves. A green line indicates that the horizontal member is well-joined to the two columns, a yellow line indicates that the horizontal member is undergoing separation from one of the two columns, and a red line indicates that the horizontal member is undergoing separation from both columns.

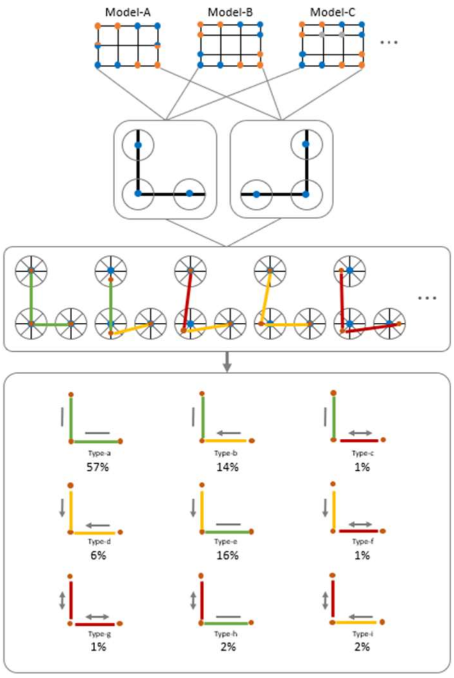

Figure 48. Three-point column movement (front). This shows the movement of the left and right corner columns at the front. The color legend is the same as that shown in Figure 47.

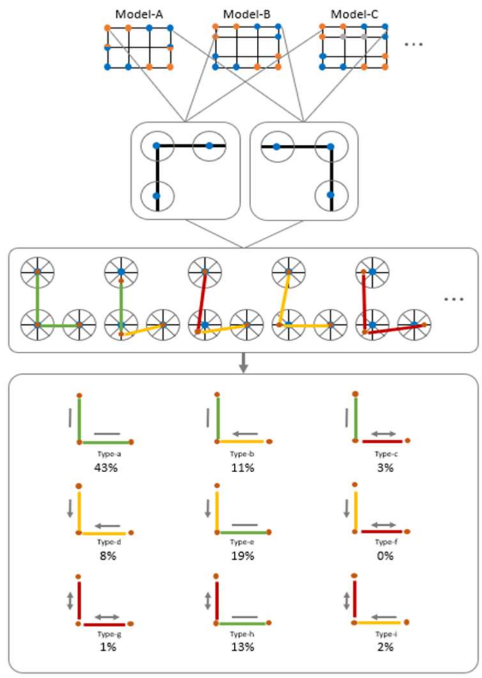

Figure 49. Three-point column movement (back). This shows the movement of the left and right corner columns at the back. The color legend is the same as that shown in Figure 47.

As shown in Figure 47, the joining strength of two horizontal members centered on the corner column can be checked, and the joining strength is strong, with a rate of 88%, for Type-a, Type-b, Type-d, and Type-e. However, 13% of Type-b, 7% of Type-d, and 18% of Type-e show a good connection with the corner column but a loss of connection with the average columns.

4.4. Analyzing Four-Point Column Movement

4.4.1. Corners

To check the column movement in the entire shape of the hanok, four points where corner columns are located on the floor plan were connected. The stability of the horizontal member is expressed according to the movement of the columns, where green indicates columns in a fixed state, yellow indicates a decrease in the joining strength in one direction, and red indicates a decrease in the joining strength in both directions. As shown in Figure 50, there are up to 81 patterns of four-point column movement. The 69 hanoks studied were categorized into 22 patterns (Figures 51–53). Of the 69 hanoks, 23 buildings (33%) were found to be stable, while 46 buildings (67%) were found to be unstable.

4.4.2. Daedlebo Direction

The movement of columns in the center of a hanok connecting two average columns in the front and two average columns in the back with horizontal members was derived. As shown in Figure 54, 40 patterns were derived out of a total of 81 in the expected range. The number of buildings with solid joints was low at 16 (16.4%), and the number of buildings undergoing separation from the horizontal member was high at 53 (83%). There are 15 patterns that fall under model A, 7 patterns that fall under model B, and 11 patterns that fall under model C (Figures 55–57). When comparing joining strength in terms of the average scale of the building by models, they rank as follows: model A < model B ≦ model C. This means that the smaller the scale, the more sensitive the movement of the columns. Model B is a structure in which a single Daedlebo is joined, and model C is a structure in which two Daedlebos are joined to form a large space. Compared with model B, model C indicates that the separation of the Daedlebo is more unstable. Although there are cases of using steel to reinforce the spacing condition, it is rare to diagnose the entire building and check the direction of movement for reinforcement. In addition, due to the characteristics of a hanok, not using steel is a major feature; however, inaccurately diagnosed exposed steel reinforcement seems to be heterogeneous, as well as being a factor that increases the variability in column movement (Figures 58 and 59).

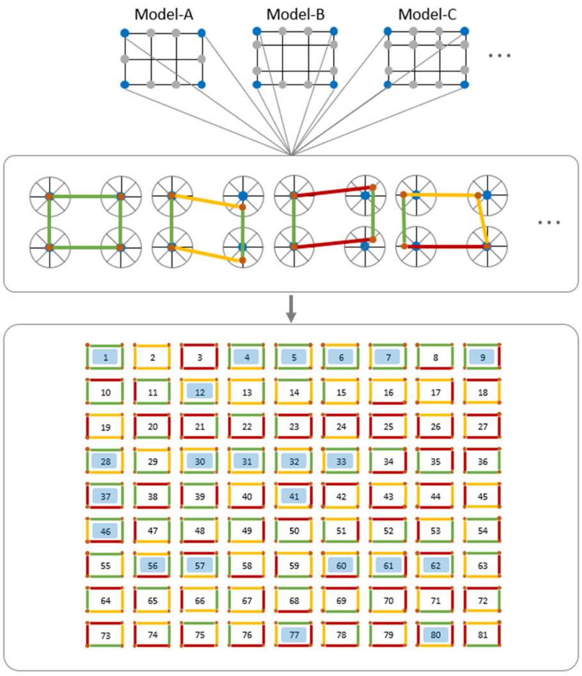

Figure 50. Four-point column movement synthesis (corner). To represent the overall column movement in a hanok, the movements of the four corner columns are synthesized. A green line indicates that the horizontal member is well-joined to the two columns, a yellow line indicates that the horizontal member is undergoing separation from one of the two columns, and a red line indicates that the horizontal member is undergoing separation from both columns. The labels 1–81 represent the maximum number of variations that horizontal members joined to columns can represent, which is 81 patterns. The blue backgrounds of the numbers represent the conditions of the 69 hanoks studied, and 22 patterns were identified: 1, 4, 5, 6, 7, 9, 12, 28, 30, 31, 32, 33, 37, 41, 46, 56, 57, 60, 61, 62, 77 and 80.

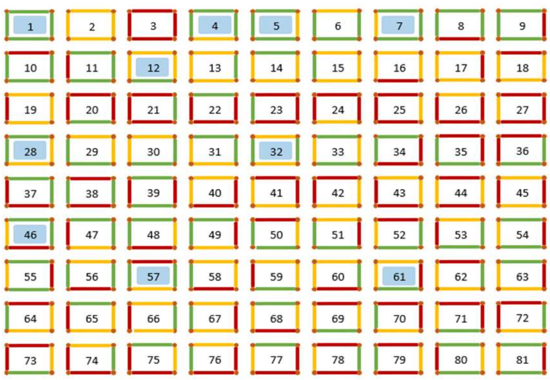

Figure 51. Model A. Model A has 10 patterns of column movement: 1, 4, 5, 7, 12, 28, 32, 46, 57, and 61. The color legend is the same as that shown in Figure 50.

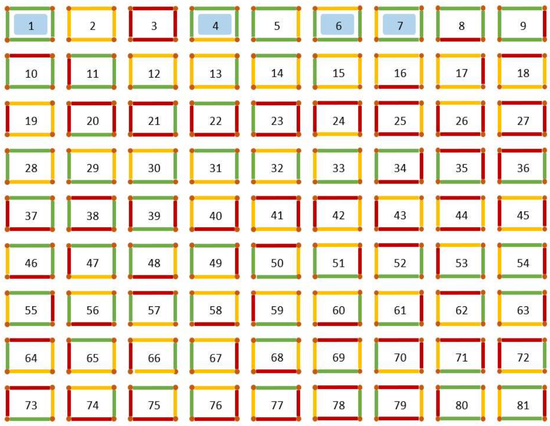

Figure 52. Model B. Model B has 4 patterns of column movement: 1, 4, 6, and 7. The color legend is the same as that shown in Figure 50.

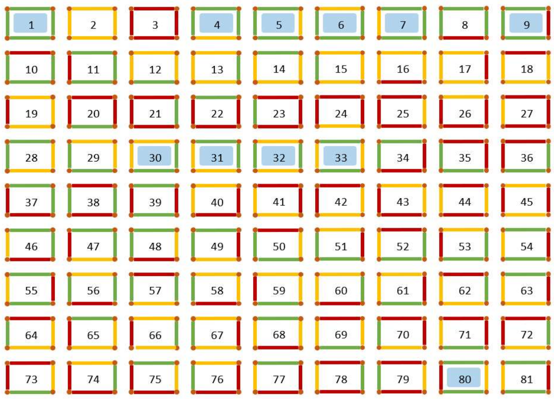

Figure 53. Model C. Model C has 11 patterns of column movement: 1, 4, 5, 6, 7, 9, 30, 31, 32, 33, and 80. The color legend is the same as that shown in Figure 50.

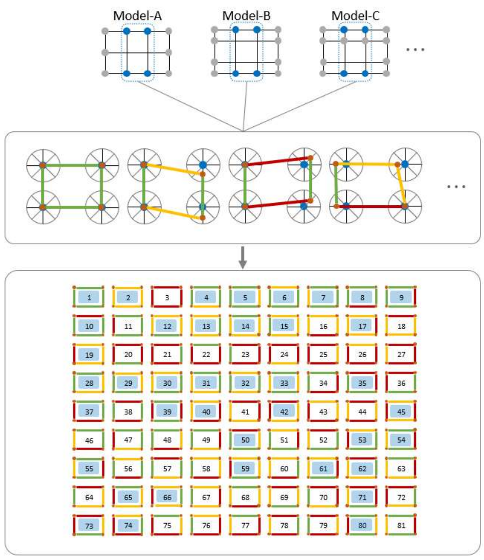

Figure 54. Four-point column movement synthesis (Daedlebo). The movements of four columns in the center of the hanok, two front columns and two back columns, were synthesized. Out of 81 patterns, 40 patterns emerged: 1, 2, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14, 15, 17, 19, 28, 29, 30, 31, 32, 33, 35, 37, 39, 40, 42, 45, 50, 53, 54, 55, 59, 61, 62, 65, 66, 71, 73, 74, and 80. This is more than the number of corner column patterns in Figure 50, indicating that there are more variables in the direction of movement of the center column.

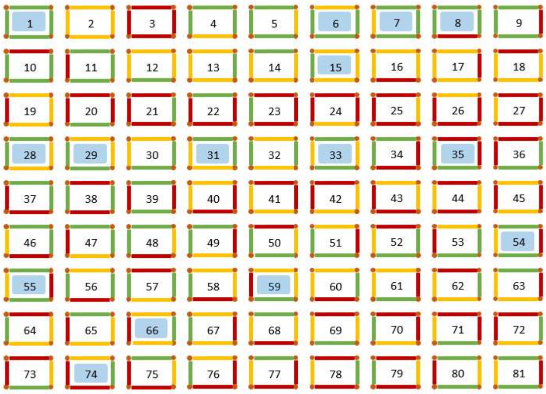

Figure 55. Model A. Model A has 15 patterns of column movement: 1, 6, 7, 8, 15, 28, 29, 31, 33, 35, 54, 55, 59, 66, and 74.

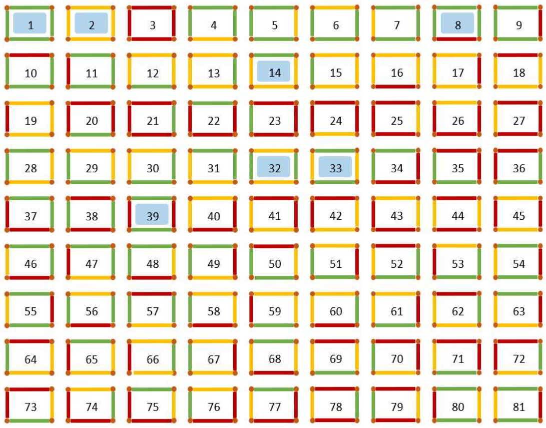

Figure 56. Model B. Model B has 7 patterns of column movement: 1, 2, 8, 14, 32, 33, and 39.

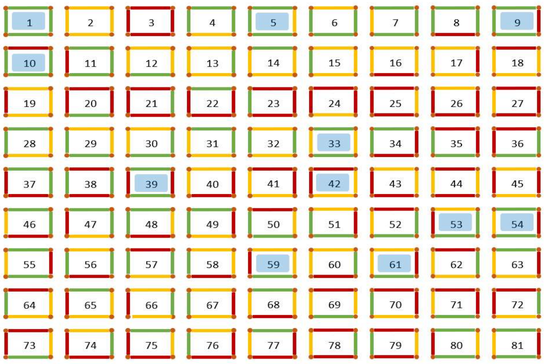

Figure 57. Model C. Model C has 11 patterns of column movement: 1, 5, 9, 10, 33, 39, 42, 53, 54, 59, and 61.

Figure 58. Matbo. This is a column inside a hanok, and the left and right horizontal members are joined around the column. This is an example of using steel (white circle) to prevent separation due to the aging of the connection. (Treasure: Seoul Heunginjimun).

Figure 59. Pyeongbang. Pyeongbang is a horizontal member placed on an external column. This is an example of reinforcing the joints with "ㄷ"-shaped steel (white circle) to prevent the pyeongbangs from separating. (Treasure: Daegu pagyesa wontongjeon).

5. Conclusions

In order to preserve the old cultural heritage of hanok architecture, defects were repaired to preserve them. However, the repairs also caused other problems. It was not known whether the defects found were primary or secondary. This study focuses on the movement of the columns, which is the stage just before a building collapses. In order to observe the movement of the columns, it was necessary to prioritize comparison with similar buildings and the most common form of hanok architecture. Therefore, 69 hanoks were selected by identifying architectural similarities using a database of hanok architectural attributes. Similar hanoks were clustered based on UMAP and DBSCAN, and column movement patterns were derived in one-point, two-point, three-point, and four-point formats that reflected the characteristics of the hanoks.

The findings are as follows:

First, although the characteristics of hanoks are different in detail, the similarity test performed by building a DB of building attributes showed a 90% accuracy rate, indicating that the similarity among buildings is high. The importance of similarity is to output patterns of movement phenomena in each building.

Second, nine different movement directions were derived from one-point column movement, including a column with no movement. Although the movement directions were different depending on the location of each column, similar patterns were found. In addition, similar movement phenomena were confirmed in comparison with similar buildings depending on the location of the columns. In Figure 32, it can be seen that the "$\boxed{\swarrow}$"

direction was relatively uncommon in the movement of a corner column. In general, the movement of columns in the "↑ and →" or "$\boxed{\nwarrow}$ and $\boxed{\searrow}$" directions was generally stronger in the direction of average columns. The front average columns were more unstable than the back average columns, and the right average columns were more unstable than the left average columns.

Third, in the movement of two-point columns, the direction of the column's movement was different when the strength of joining with the member was reduced. This means that the joining between the members was undergoing separation. In hanoks, which are structures that are built using joint techniques without using nails, the columns move in different directions, which is a very dangerous condition. When the column movement was checked against the direction of the beam and the direction of the Dori, different directions of movement were found, indicating that the joints connecting with the horizontal member had lost their joining strength.

Fourth, in the movement of three-point columns, at the connection of a corner column and two average columns corresponding to the corners of a building, if the joining strength with one or more members is reduced, the columns will lean in the "$\boxed{\nwarrow}$ and $\boxed{\searrow}$" direction. Due to the characteristics of hanoks, the joining strength of the horizontal members located at the corner column is higher than the joining strength of the horizontal members joining the average columns. The horizontal members of the corner column correspond to the cross-joint technique, while the horizontal members joining the average columns correspond to the unidirectional joint technique. The experiments in this study showed that the average column joints are the most vulnerable, and the movement of the corner columns is affected by the state of the average column joints.

Fifth, in terms of the movement of four-point columns, the overall movement of the building and the movement of the four columns in the center of the building were analyzed, and 40 patterns were identified out of a total of 81 ranges. The smaller buildings, such as model A, showed a variety of column movements, while model B had a relatively stable ratio and structure, and model C was found to have a weak connection with the Daedlebo.

This study aims to identify and diagnose expected causes of structural defects before they occur by deriving common patterns of column movement in hanoks. This will contribute to the effective preservation and management of hanok cultural heritage by finding and diagnosing the exact causes of deterioration before repairing the hanok, thereby allowing appropriate repairs to be carried out. The limitation of this study is that it is necessary to track the movement of the columns for a single building more than once to observe the detailed changes after measurement. In addition, the data should be extracted by observing the changes in the columns before and after the repair of the hanok building over a period of time. This study will help to find overlapping causes by comparing honks with newly occurred defects. The next follow-up study will find and trace back natural factors (temperature, humidity, natural disasters, aging, etc.) and man-made factors (design, construction, management, etc.) that affect the movement of columns and combine them with this study to clarify the causes of defects more clearly.

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Conflicts of Interest: The author declares no conflicts of interest.

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