Application of and Changes in Construction Principles and Joint Methods in the Wooden Architecture of the Joseon Era: A Case Study on the Sungnyemun Gate in Seoul

Jin Hong Park¹, Young Jae Kim²* and Dong Soo Han³

¹Ph.D. Candidate, Department of Architecture, Hanyang University, Korea
²Assistant Professor, Department of Heritage Conservation and Restoration, Korea National University of Cultural Heritage, Korea
³Professor, Department of Architecture, Hanyang University, Korea

Abstract
Various efforts are needed to understand the construction principle of wooden architecture in the pre-modern era, as theoretical literature on this topic is lacking. This study shows that wooden construction methods are divided into two categories consisting of piled-up and integrated structures. The primary difference between the two categories is that the former is supported by a structural system weighted by a load from above, whereas the latter involves strengthening of the combination itself. In Korea, the framed system seen in a partially integrated structure is confirmed based on the structure of a piled-up framework. The Sungnyemun Gate is a representative example, and exemplifies piled-up techniques with a structural stability that is grounded by the load. However, the building's interior is characterized by the active adoption of pass-through columns employed in the integrated structure. Such structural compromise results in great changes. When the authors examine the joining parts of major timber-framed structures like the Sungnyemun Gate, at its completion, it had weak joining connections in the piled-up structure; however, after several repairs, it was strengthened with an integrated structure. This thesis examines a regional peculiarity of the wooden architecture that adopted eclectic styles based on the piled-up structure.

Keywords: piled-up structure; integrated structure; joint methods; reinforcing solidarity; Sungnyemun Gate

1. Introduction
In traditional wooden architecture, the construction process was regarded as a secondary act in the implementation of the planned architectural form. The process, however, had an effect on determining the method used for construction of the whole structure to the details of its frame. More importantly, the process has an important meaning, as it contains clues in understanding the construction principles. Recently, there have been a series of studies on the construction principles of East Asian wooden architecture.¹ Although opinions on these studies differ, scholars agree that there are two types: a framed structure and a piled-up structure. However, these studies are approaches from an analytical point of view, enabled by a thought process based on the interpretation of historic sites and the structural shapes of buildings; they have not endeavored analysis of actual buildings. Since the two construction methods are mixed in case studies, it is not easy to distinguish their synthesis under close scrutiny; so far studies have demonstrated significant gaps in theory and practice.

In this study, based on the construction method of wooden architecture, construction methods are divided into the piled-up method and the integrated method, and the concept of the joint combination is confirmed. The division of the construction principle has become clearer, and the dependence of the joint method on the construction principle is confirmed. In Korea's case, it can be seen that the piled-up and horizontal-framed structure are employed as the basis of an entire framework, and the increase in the number of jointing elements in the integrated structure at the later stages is also confirmed.

The Sungnyemun Gate is a two-storied wooden building above masonry stone construction and is this study's main research focus. Upon examination, a pile-up structure structural stability by means of the load is observed. However, it is characterized by the active use of high columns (pass-through columns), which create an integrated structure inside the gate. First, the Sungnyemun Gate has a faithful record as an official building. Second, it was built at the beginning of the Joseon Dynasty, and it is possible to trace its evolution to the present through scientific analysis...
of aspects such as building techniques and tree-ring dating. Third, it has influenced many buildings such as the Hwaseong Fortress Paldalmoon Gate in Suwon and the Hanyangdoseong Heunginjimun Gate in Seoul, and can be regarded as the standard of Joseon Dynasty architecture. Thus, the Sungnyemun Gate is the ideal case to understand how the two construction principles have been applied and adjusted in accordance with changes to joint methods over time.

The purpose of this paper is to clarify the regional specificity of Korean wooden architecture in the Joseon Dynasty through the change of the construction principle and the method of construction of wooden architecture. The research method first defines the generalized construction principle of wooden architecture according to the construction viewpoint. This paper provides a framework for the analysis by examining the relationship between the connection concept and the load of the connected joints. The authors will examine the ways of construction in the repair process changes through comparison of the Sungnyemun Gate and other related examples, and will also analyze the extent to which this resulted in the local peculiarity exemplified by the monuments of the Joseon Dynasty, which trickled into Korea from China during the fourteenth century.

Table 1. Concept of Piled-up and Integrated Structure

<table>
<thead>
<tr>
<th>Division</th>
<th>Method used in the Piled-up Structure</th>
<th>Method of Raising the Framed Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure method</td>
<td>Piled-up (Horizontal)</td>
<td>Integrated</td>
</tr>
<tr>
<td>Structural strengthening</td>
<td>Strengthening the upper weight</td>
<td>Strengthening the bonding between wooden members</td>
</tr>
<tr>
<td>Force</td>
<td>Oriented by compression Force (using gravity)</td>
<td>Oriented by tensile force (between wooden members)</td>
</tr>
<tr>
<td>Use of pillars</td>
<td>Cut-off columns (pillars divided into each floor)</td>
<td>Pass-through columns (high columns, columns connected to a roof frame)</td>
</tr>
<tr>
<td>Load of the upper building structure</td>
<td>Weighted roof type</td>
<td>Lightweight roof type</td>
</tr>
</tbody>
</table>

Fig.1. Research Procedure Diagram

2. Construction Principle and Concept of Joint Combination According to Construction Methods

2.1 Construction Principle According to the Construction Method of Wooden Buildings

Construction methods of wooden architecture can be categorized as follows. The first method comprises a piled-up structure in which the timber-framed layers with a well framework are stacked one on top of the other from the bottom to the top. The piled-up structure mainly uses a weighted roof in a classical manner using gravity. It is similar in concept to a masonry structure, except that in masonry construction, bricks are the main material and it employs the wet construction method, that is, application of an adhesive such as mortar. In contrast, the piled-up method uses wooden members as the main material and follows the dry construction method with tenon-and-mortise joints. A different structural system emerges according to the linkage methods used with wooden members and their strength. The range of the piled-up structure is based on the well framework (Jinggan) comprising horizontally laid logs with interlaced corners in the shape of a well. In a broad sense, it is also possible to include the post beam and strut framework (Tailiang), in which each wooden member is raised horizontally and vertically (Fig.2. ③). In the bracket set system, which is one of the characteristics of wooden architecture in East Asia, the piled-up method is employed in the construction of crossing bracket arms. Second, the integrated structure is first assembled and then raised on the ground (using a method to raise a timber-framed structure). Maintaining a stable balance by consolidating the mutual solidarity between each wooden member is desirable in this method; it is noteworthy that such a process remains "integrated" and is comparable to a reinforced concrete structure, in which the reinforcing bars are integrated seamlessly with concrete from the foundation to the upper post-and-beam structures. However, in the case of a wooden structure, the difference is that the property of each individual member is preserved, although individual members move together by fitting and jointing to strengthen the binding. Because it is assembled, raised, and connected on the ground without using a scaffold, the integrated structure uses pass-through pillars that penetrate to a roof. The top load of the post-and-lintel construction to make a roof framework employs a minimal lightweight structure. Examples include the post beam and tie framework (Chuandou) in southern China's Yunnan Province and the timber framework using Western wooden members such as trusses and bents. (Fig.2. ⑤)
2.2 Concept of Joint Combination in the Construction Principle of Wooden Buildings

In the wooden framed structure, the horizontal tie beam members are mortised directly into or tenoned through several columns by combining to form a structure. Joints are important in determining structural strength. In the two structural principles, the principle of "combination of wooden members" is similar, but the strength of binding is significantly different between each member.

The piled-up structure is maintained in the horizontal or vertical orientation so that independence between the upper and lower members is maintained. In prehistoric times, the joints of the upper and lower members were tied with rope and finished with rattan and kudzu; however, the strength of the piled-up combination was weaker than that of the integrated synthesis of a single body (Fig.3. Ⓐ). In contrast, the binding in the integrated structure is a three-dimensional combination in which members of the X, Y, and Z axes cross each other at one point for strong binding. This is strongly intended to suppress the movement between the members through the binding of the integrated members when acted on by external stress (Fig.3. Ⓑ).

Roof loads are important in structural design in the binding between the wooden members. As the piled-up structure is a weighted roof, the post beam and strut framework emphasizing a "piled-up" system are stabilized based on the compressive force. Therefore, the cross-sectional loss should be minimized by joint combination between the wooden members. However, as the integrated structure has a lightweight roof, cross-sectional loss has a relatively small effect on the amalgamation of each member, and the joint method, such as the tenon-and-mortise, is developed to strengthen the binding. Additional reinforcing materials, such as wooden pegs and wedges, and iron fittings are used actively in the modern period.

3. Application of the Construction Principle in Wooden Architecture Since the Early Goryeo

In theory, the two concepts discussed above are clearly distinguished. However, in practice, there is a limit to the clear distinction because the concept of the piled-up structure is applied based on the integrated structure, or the integrated structure incorporates the piled-up structure.

The oldest building in Korea, namely, the Geukrakjeon Hall at Bongjeongsa Temple, has a piled-up structural system with a gambrel roof and pillar-top bracket sets. The entire composition of the inner and outer pillars follows different methods. The inner structure is a typical piled-up structure constructed by erecting cut-off columns and then locating transverse beams overlaid on top of them (Fig.4. Ⓐ). Meanwhile, the outer structure of the left and right side applied the construction principle of the integrated structural system by using longitudinal beams penetrating the pass-through high columns at the center with transverse tie beams penetrating the columns (Fig.4. Ⓑ).

The Daeungjeon Hall ("hall of the great Buddha") of the Joseon Dynasty was built in 1435, around the same time as the Sungnyemun Gate, the subject of this study, and is similar to it in terms of techniques, such as the shape of the brackets. The structure is based on the logic of a piled-up structure in which pillars are laid out on the outside of the building. The bracket set is surmounted on the pillars, stacking longitudinal beams, struts, and purlins to make the roof frame (Fig.4. Ⓒ). However, in the sectional configuration of the central bay, pass-through high columns are placed behind the Buddha's canopy, with wooden beams penetrating the columns (Fig.4. Ⓓ).

From these case studies, the authors learn that wooden buildings in Korea used pass-through pillars (direct connection effectively on loads from the rooftop to the foundation stone) and strengthened the bindings in the integrated structural framework emphasizing the piled-up structure. This compromise appeared in buildings constructed around the 13th century, and it seems to have changed in later years by utilizing the mutual advantages positively.

Fig.2. Examples of the Construction Principles of Wooden Architecture

Fig.3. Construction Method of Wooden Structure and Concept of Solidarity
In contrast, in the late Goryeo Dynasty and the early Joseon Dynasty, both the Geukrakjeon Hall and the Daeungjeon Hall at Bongjeongsa Temple adopt a weak coupling scheme in the incorporation of the wooden members, applying the piled-up construction principle. In the combination of columns and tie beams, a coupling scheme is identified, in which cohesion is enhanced by cutting linear grooves on top of the columns and then putting together the transverse tie beams on them; meanwhile, the bracket sets are combined using crossing bracket arms. Such a joint method has a disadvantage in that the coupling force is lowered at a portion where the top load is not transmitted.

Problems arise when the beams and the pass-through columns are joined. The fact that there is no reinforcement, such as wooden pegs and iron ties, confirms it was not needed because of the strong bonds with integrated joints based on the principle of the piled-up structure as per the technicians of the time (Fig. 5. ⓐ, ⓑ). However, in later years, new attempts were made to strengthen the ties. The joint method of pillars with column-top tie beams is a relatively early method. The Daeungjeon Hall (1308) at Sudeoksa Temple employs a tenon joint system, with tie beams penetrating the columns and crossing bracket arms in the upper part of the pillars, and reinforcing the tie beams (Fig. 5. ⓒ). Since then, this method has been used universally in buildings with column-top bracketing. However, in the construction method, it has a piled-up structure, and the bonding force is lower than that of the integrated structure.

Building types for strengthening solidarity similar to the integrated structure are seen around the middle of the Joseon Dynasty. Typically, both the Daeungjeon (1679) and the Eungjinjeon (1751) Halls at Yulgoksa and Miwangsa Temples, respectively, employ a combination of outer pillars with dovetailed tenon joints at the end of the tie beams (Fig. 5. ⓔ). Apart from these halls, in the Daeungjeon (1645) and the Gunjeonjeon (1867) Halls at Tongdosa Temple and Gyeongbokgung Palace, respectively, a more advanced method is used. The former chooses a tenon joint with tie beams penetrating the columns, plus wooden pegs, whereas the latter has a dovetailed tenon joint with the tie beam penetrating the column crossing the bracket arms (Fig. 5. ⓓ, ⓕ).

The "compromise" is a natural result derived from the process of acknowledging the differences in the contradictory logic structures and then finding a point of agreement. As the culture of the domestic environment, technology, and structural system are expressed by a mutual fusion of subject and object through interaction with the outside, various results can be derived depending on the conditions of construction. Although there could be similar conditions, the manner in which these compromises are applied is considered important. In the next section, with the Sungnyemun Gate as the main subject of this study, the authors examine how the contrasting logic of the structure between the piled-up and the integrated method is compromised and manifested from detailed joint connections.

4. Characteristics and Changes of the Framework Structure of the Sungnyemun Gate in the Joseon Period

4.1 Use and Influence of Pass-through Columns in the Piled-up Structure

The Sungnyemun Gate is a five-by-two-bay hall with pass-through high columns at the center connecting the upper and lower floors; the entire structure is strengthened by the pass-through high columns at each corner (Fig. 6. ⓐ). The upper and lower floors are integrated by the pass-through high columns rather than by the division of upper and lower
floors independently. Considering the characteristics of the gate pavilion, which is built on the masonry construction and has a narrow side, it seemingly uses the structural strength of the external lateral force (Fig. 6. b). However, there is a clear difference in the interior and exterior construction methods, with the outside stacking vertical (columns) and horizontal (bracket arms, beams, etc.) materials, and the inside having continuous columns as seen in the integrated structure. The anisotropy in which the timber-framed structure appears to be a drying shrinkage has many effects after the building is completed. In addition, owing to the compression shrinkage of the members under its own weighted roof, the instability of the building, caused by the difference in construction methods, becomes more pronounced.

In the late Joseon Dynasty, several buildings followed the structural system of the Sungnyemun Gate, such as the Paldalmon (1796) and the Heunginjimun (1869) Gates. The Paldalmon Gate is an example of the late middle Joseon Dynasty built in the suburbs of Seoul. Although a time difference exists of more than 300 years between this gate and the Sungnyemun Gate, it is fundamentally the same in the plan composition and the construction method. It can be inferred that the Paldalmon Gate was designed using the Sungnyemun Gate as a model. On the other hand, new structural elements were added. The Paldalmon Gate does not use the corner high columns in the four corners of the lower floor. Off-corner tie beams (gwijabibo) are used in diagonal directions at 45-degree angles above bracket sets on the four corners, and corner columns were installed on the tie beams on the upper floor. These techniques occurred in multi-storied buildings around the 17th century, including the Palsangjeon Hall at Beopjusa Temple. The application of the off-corner tie beams is a way to save members instead of using high corner columns, and is an advantageous technique in the effective utilization of the corner space of the lower floor. It also strengthened the whole structure by holding the unstable corner parts with the tie beams. However, the use of pass-through columns in the interior of the building did not change. The mixture of the two methods triggered structural problems; rafters in the upper floors fell off and beams hung down. These issues prompted repair work in 2010. (Fig.7. a) Also, the Heunginjimun Gate (1869), which was reconstructed in the 19th century, shows the new stylistic expressions enchased on the surface of bracket sets, which reflected the circumstances of the time. However, they all adopted a similar structure to that of the Sungnyemun Gate. (Fig. 7. b)

In addition, the pass-through columns retained and then combined with the old techniques were evident throughout the Joseon Dynasty in the active use of high columns and corner high columns within multi-storied halls and important official buildings such as the Injeongjeon Hall (1803) of Changdeokgung Palace and the Geunjeongjeon Hall (1867) of Gyeongbok Palace (Fig. 8. a, b).

These construction methods are in line with the conservative tendencies of the Joseon Dynasty, which emphasized old traditions from a Confucian point of view. Although structural problems have arisen due to the employment of pass-through columns, the continuous application of these old techniques seems to be a matter of the builders' consciousness of the time, which was based on the complement of repair rather than the object of improvement.
Later, there were repair works in 1448 (Sejong 30) and 1479 (Seongjong 10). Although records of another repair work are not confirmed, apparently it happened in 1868 (Gojong 5). The existing records show structural problems, such as broken beams and pillars. There were two major repair works every 30 to 40 years after its completion, and it can be assumed that there were structural changes to resolve these matters.

4.2 Changes in Joint Methods

The joints between the pillars and tie beam are placed in the upper part of the pillars in a linear groove. The tie beams penetrating the pillars are joined together by a rake joint (Fig. 9. Ⓐ). It is understood that this is the basic construction method of the piled-up structural system, which maintains the bonding force between the members by using the upper vertical load. However, when moment works in the connection point due to the imbalance of the upper framed-structure, breaks and shrinks appear in the upper part of the columns thereby reducing the bonding force between the wooden members.

An upper joint on top of a lower column of the Sungnyemun Gate (1398)
An upper joint on top of a lower column of the Suwon Paldalmun Gate (1796)

The Geukrakjeon and the Daeungjeon Halls at Bongjeongsa Temple, which were built in the late Goryeo and the early Joseon periods, respectively, show the same construction method. In the late Joseon era, a change occurred in the way solidarity was enhanced. For example, the Paldalmun and the Heunginjimun Gates bind together the columns and tie beams with a dovetailed tenon joint, and carved bracket arms (anchogong) between them were installed in a crosswise direction to increase the binding force. (Fig. 9. Ⓑ). The Sungnyemun Gate also changed in 1868. The repair work was complemented with iron strings. Then, in 1961, the iron strings were removed and replaced by dovetailed tenon joints (Fig. 9. Ⓑ).

The synthesis of the longitudinal beams with the pass-through high column was carried out through the tenon-and-mortise joints on both ends of the beam (Fig. 10. Ⓐ). This is vulnerable to tensile forces. However, it is a method for maintaining the binding force by using the frictional force between the self-weight and the member of the beam. It is the same structural principle as that used in the upper part of the column. In the nineteenth century, iron members were actively used. Iron bands were stuck between both beams to prevent separation, and half bracket arms were placed on the lower part to attempt aggressive reinforcement through the coupling.

In the repair work in 1961, half bracket arms and iron strings were removed; wooden pegs were used to reinforce the connections, and long rectangular members were attached to both sides of the columns (Fig. 10. Ⓐ). In later years, strings and pegs were used to make a strong amalgamation, a process similar to an integrated structure. Nonetheless, it had the secondary purpose of complementing the variation of member contraction and relaxation.

The piled-up structure, as mentioned above, is stabilized by applying a heavy load from the top for a strong combination. However, when the joint hole is pierced at the point where the pass-through high columns are joined to the other members in the piled-up structure, a sectional weakening appears, and this can become a structural weak point. The heavier the overhead load, the more contradictory the structural problem appears. The joint connections of the existing corner cantilever in the lower floor with the corner high columns were combined with the method of tenon joints penetrating the high columns, and the rear roots of the protruded corner cantilever were fixed adding the tenon joint above the corner exterior purlins (Fig. 11. 
In the repair work carried out in the 1960s, tenon-and-mortise joints were fastened with iron pegs to compensate for large defects in the cross-section loss. The pass-through columns at each corner were joined with members, such as tie beams and purlin support as well as corner cantilevers, resulting in cross-sectional loss along the joint grooves. These were seen as measures to minimize structural problems.

The most apparent aspect of these issues is evinced by the main joints of pillars, beams, corner cantilevers, and rafters. The methods for fitting the tie-beams to the linear groove of the upper part of the columns and combining the beams with the pass-through high column (including tenon-and-mortise joints) are typical methods, and can be seen in the piled-up structure which maintains the binding force by the top load. In the repairs performed in the 20th century, methods for connecting main joints were replaced by dovetailed tenon joints. The wooden pegs and iron hardware were established to strengthen the solidarity. These were seemingly similar to the methods for consolidating an integrated structure. However, strictly speaking, they should be distinguished from the different joints in terms of their background and purpose. The alignment of corner cantilevers in the lower floor and the tenon joints of corner high columns are revealed in the integrated structure. However, during the 20th-century repairs to solve the structural problems caused by the roof weight, the combination method was modified by minimizing direct connections and by engaging wooden pegs, which are suitable for the piled-up structure.

On the contrary, the reinforcement work for the post beam and strut framework of the Sungnyemun Gate is concentrated on modern repair methods introduced in the 20th century. The technical supplementation in the invisible portion of the structure was implemented successfully whereas the architectural style was focused on part of the original form; the products of later generations were easily removed. If this structural phenomenon, which appears to be a compromise of the structural principle, is recognized with importance as the specificity of the regions and times, the approaches leading to structural problems and technical strengthening should be considered carefully in terms of their authenticity.

This study clarifies the limitation of the hypothesis by applying the method to the existing edifices while also examining the construction principles in the existing building method. In particular, the wooden buildings remaining today have not retained their original shape, and have been revised and supplemented through maintenance and repair works over time. Therefore, it is difficult to judge the past from the present appearance.

However, for Korea, the absence of theoretical literature and specialized technique materials on traditional wooden architecture make it difficult to grasp the structure through empirical research alone, and calls for various approaches to research on this topic through logical reasoning. Korean wooden architecture is characterized by an upper structure made heavy by putting soil on the roof. This is done for insulative purposes in cold regions, but fundamentally, it seems to be the result of further development of the structural system of the piled-up structure. The
limitations of the piled-up structure are seemingly complemented by the application of various methods, such as the use of high columns and strengthening of the joint connection.

In this study, the authors have examined the main cases of official architecture. However, they think that various interpretations are possible through expansion of the scope to religious and residential architecture. Therefore, they anticipate that this study will clarify the distinct characteristics of the sphere of wooden architecture. The authors expect to identify the regional specificity of Korean wooden architecture by further broadening the scope of investigation and analysis in the future.

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Notes
The existing studies on the construction principle of wooden architecture are as follows. Zhang Siqing (2007) insisted dialectic tectonic traditions evolved by embracing the unique local natural and cultural environment through a way of thinking about the wooden structure dwelling upon the piled-up and the framed types. Lee Kangmin (2010) determined the structural principle that was classified by the purlin and the rafter structure. Lee noted that the horizontal, vertical, and diagonal members created a sloped roof, and pointed out that the two principles based on purlins and rafters evolved in an appropriate mix with inverted-V-shaped braces, bracket sets with cantilevers and inverted-V-shaped trusses. Kim Youngjae (2017) discussed two construction methods (the timber-based framed system and the earth-and-wood piled-up system) through the comparison of ancient Chinese building sites in terms of tectonic traditions. Kim argued that the two tectonic traditions gradually integrated and merged into one over time, and that the advantages of both 'piled-up' and 'framed' wooden structures became dominant and continued to evolve through selective adoption between regions and times. These studies examine the effect of the research endeavors from the point of view of building construction, which later influenced the tectonic traditions of other Asian countries. S. Q. Zhang, (Apr. 2007) "On the type and evolvement of ancient building structure from the aspect of tectonic thinking" [Congjiangou siwei kan gudai jianzhu jiegou de xingzhi yu yanhua], pp.87-90; K. M. Lee (2009), The Building principles and typology of roof structure in the East Asian Wood Architecture, PhD Dissertation, Seoul: Seoul National University; Y. J. Kim et al. (2017), "Tectonic Traditions in Ancient Chinese Architecture, and Their Development," Journal of Asian Architecture and Building Engineering 16, no. 1, pp.31-38.

1. Y. J. Kim et al. (2017), op. cit., p.36.
2. Ibid., p.37.
4. The Sungnyemun Gate was constructed in 1398 (Taeto 7). There were two repair works in 1448 (Sejong 30) and 1479 (Seongjong 10) after its completion. Afterward, the repair records were not confirmed until 1688 (Gojong 5). However, in the absence of records, the authors cannot say that there were no repair works for 400 years. After the liberation from Japanese rule in 1945, there was a complete dismantlement and repair work in 1961. After an arsonist set fire to the Sungnyemun Gate in 2008, it was restored in 2013.
5. The application of pass-through high columns at each corner of the Sungnyemun Gate is a remarkable feature. The method is confirmed only in official buildings, which are actively used in palace and fortress buildings in the Joseon period: The Sungnyemun Gate (1398); the Heunginjimun Gate (1869); the Gwanghwamun Gate (1865) at Gyeongbok Palace; the Injeongjeon Hall (1803) at Changdeokgung Palace; the Gunjeongjeon Hall (1867) at Gyeongbok Palace; the Junghwajeon Hall (1906) at Deoksugung Palace.

References
2) Zhang, S. Q. (Apr. 2007) "On the type and evolvement of ancient building structure from the aspect of tectonic thinking" [Congjiangou siwei kan gudai jianzhu jiegou di leixing yu yanhua], Jiaozhuzhi, pp.87-90.