Structural Characteristics of Carian Rock-Cut Tombs: The Effect of Discrepancy Between the Connecting Part and the Back Passage

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Abstract. Studies of the history of ancient Greek architecture have primarily covered public architecture such as temples and stoa, which had similar architectural forms and structures. Consequently, many studies have been conducted from a formalistic perspective or have focused on design related aspects, and ancient Greek architects' conception of the structure have hardly been elucidated. Analyzing tombs of the Hellenistic age which have diverse architectural forms and structures is considered to shed light on how ancient Greek architects conceived the relation between structure and design.

Against the backdrop described above, with the elucidation of ancient architectural engineers' conception of structure and design as the ultimate goal, this paper analyzes the impact on the structural characteristics of rock-cut tombs by the 'position of the connecting part' and the 'height of the back passage of a rock-cut tomb' by performing structural analysis using a three-dimensional FEM analysis program. As a result, above all, it was revealed that the maximum principal stress could be minimized by balancing the position of the connecting part and the height of the back passage of a rock-cut tomb.

Keywords: Ancient Greece · Caria · Rock-cut tomb · Structural properties · Three-dimensional FEM analysis

1 The Background of This Study

Ancient Greek architecture has traditionally been said to be mainly characterized by uniformity, with each type of structure mostly having a definite corresponding architectural form, as seen in structures such as temples and stoa. Tombs of the Hellenistic age in the Mediterranean world have such multifarious architectural forms that there are said to be no two tombs that are exactly alike [1]. It is not difficult to imagine that these multifarious architectural forms developed for tombs of the Hellenistic age and a new sense of value approving them greatly contributed to later Roman architecture, for instance, by providing multifarious architectural languages and universalizing the freedom of choosing any of those languages. I have been working on tombs of the Hellenistic age for the major purpose of systematizing Hellenistic tombs and situating them

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in the history of architecture in light of the ‘peculiarity of Hellenistic tombs as ancient Greek architecture’ and a ‘possibility of their contribution to Roman architecture’ [2].

In the course of conducting this research on Hellenistic tombs, tombs were found that had diverse structures not found in other types of Greek architecture than tombs. Examples include Grave Monument III in Messene, which has a concave conical roof, and rock-cut tombs [3] in Caria [4] made by excavating a rock cliff (Fig. 1). Studies of the history of ancient Greek architecture have primarily covered public architecture such as temples and stoa, with numerous studies conducted from a formalistic perspective or on design methods by focusing on design related aspects. Consequently, no light has been shed on how ancient Greek architects conceived the relation between structure and design and embodied their conception in their design. Analyzing the relationship between the design method and structural characteristics of tombs of the Hellenistic age with diverse architectural forms and structures is considered to contribute to elucidating ancient Greek architects’ conception of design and structure.

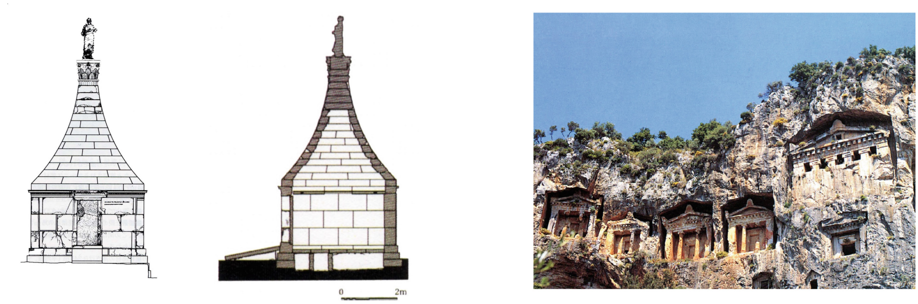

Fig. 1. An example of Hellenistic tombs (Left: Grave Monument III (Elevation, Section), Right: Rock-cut tombs in Caunus). Source: Left: Akisumi, T., RESTORATION OF THE GRAVE MONUMENT III: Architectural survey of ancient city of Messene in Greece (2), Journal of the Architectural Institute of Japan, Planning systems, No. 549, p. 288, (2001.11). Right: Hengirmen M., KAUNOS, p. 35, Baskent Repro, Ankara (1997).

Based on the above backdrop, this study is intended to shed light on the influence of differences in the ‘position of the connecting part’ and the ‘height of the back passage’ (Fig. 2) on the structural characteristics of a rock-cut tomb by focusing on rock-cut tombs in Caria with a view to elucidating ancient Greek architects’ conception of design and structure.

2 Method

The effects of differences in the ‘position of the connecting part’ and the ‘height of the back passage’ on the structural characteristics of a rock-cut tomb are examined on the basis of the result of static-elastic stress analysis with three-dimensional solid models using the three-dimensional analysis program FEMLEEG (made by FORUM8). Note that it was decided to choose an analysis method using the linear finite element method based on the consideration that an exact analysis is not required since the purpose of

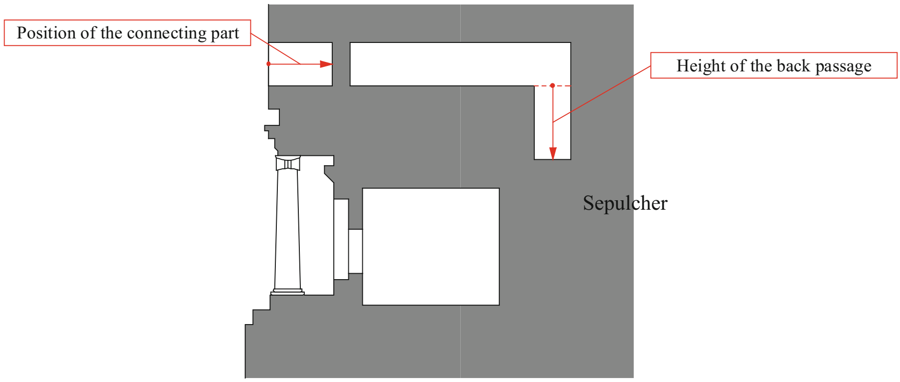

Fig. 2. A schematic diagram of the cross-section of a rock-cut tomb. Source: Created by the Author.

this study is to shed light on the relative impact of differences in architectural form on structural characteristics. In order to make it easier to find the effects on the structural characteristics of a rock-cut tomb, an analytical model is used which is uniform except for properties under examination (hereinafter referred to as the “standard model”). In creating the standard model, information on rock-cut tombs is obtained from the survey by Paavo Roos [5].

2.1 Outline of the Analytical Model

In light of the intended future evaluation of the structural reasonability of real rock-cut tombs using the result of the analysis in this study, it can be said to be desirable that the standard model have a shape similar to those of many rock-cut tombs. In order thus to find the universal shape of a rock-cut tomb, five tombs are selected each whose values of their “total width,” “total height,” and “total depth” lie near the median. Among those five tombs, Tomb C2 of Caunos (Fig. 3), which has been best preserved and does not have a peculiar shape, was chosen as the prototype for the standard model. Taking it into consideration that a rock-cut tomb is affected by the ground pressure of rock walls surrounding it, the analytical model was determined to include rock walls around a rock-cut tomb. Since, however, a rock-cut tomb is symmetrical, the model was halved to reduce the analysis load. The size of the entire model was determined as shown in Fig. 4 in order to prevent the analysis load from getting excessive and stabilize the stress distribution. The fine decoration on the tomb’s facade was omitted in modeling as it is considered to have a small effect on structural characteristics. In addition, since hexahedral elements are used in the analysis in this study, circular columns were replaced by square columns in order to stabilize the result of the analysis. Likewise, in order to stabilize the result of the analysis, a uniform mesh size was used by adjusting the dimensions of each part by 5% at maximum. Since the above three changes are similarly made in all modeling studies, they are not considered to have a significant impact on the analysis of the structural characteristics of a rock-cut tomb.

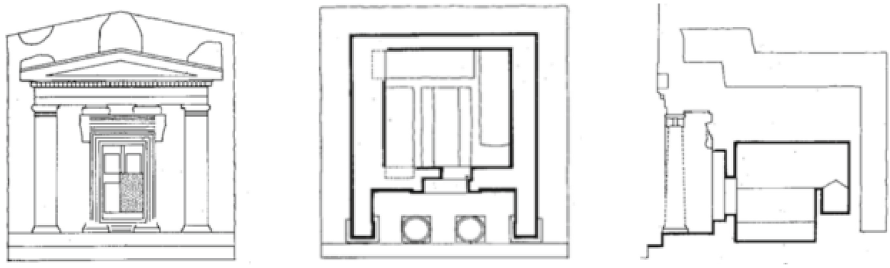

Fig. 3. Tomb C2 of Caunus (Left: Elevation, Center: Plan, Right: Cross-section). Source: Roos op. Cit. 1972, Pl.34.

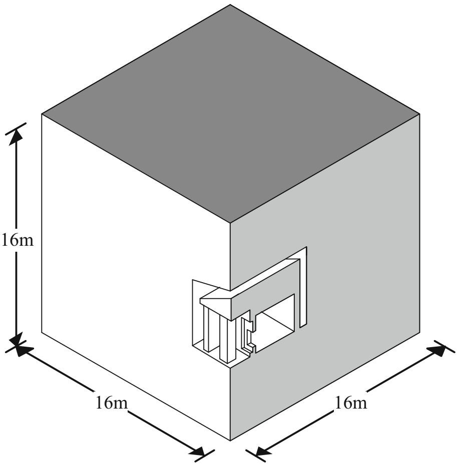

Fig. 4. A schematic diagram of the analytical model. Source: Created by the Author.

2.2 Physical Property Values and Boundary Conditions

As rock-cut tombs in Caria are built into a limestone rock wall, the physical property values of limestone are used, setting Young's modulus to 3.5×10^{10} [Pa], mass density to 2,700 [Kg/m^3], and Poisson's ratio to 0.25.

Based on the photographic measurement, there is a rock wall approximately 14 m high above Tomb C2. Still, it is difficult to replicate the weight of this rock wall itself only by the magnitude of the model due to the limit of analytical capacity. A uniformly distributed load of 1.59×10^5[N/m^2] is thus applied on the top surface of the model in this study. Besides the ground pressure from the upper part, the ground pressure from the sides and the bottom is considered to act on a model of a part of a rock wall such as the analytical model in this study. In order to replicate the ground pressure from surrounding rock walls, movable supports are used except for the top and the front, and a force having the same value as the side pressure is generated as a reaction force.

2.3 Examination of Analysis Patterns

Measured by its proportion in the 'total depth of the tomb,' the 'position of the connecting part' of an actual rock-cut tomb is mostly 10% or less from the front and about 30% at maximum. Therefore, the 'position of the connecting part' in the model is varied by an increment of '1 mesh (0.2 m)' from 0 m to 1.4 m, which corresponds to a position slightly behind one that is 30% from the front.

On the other hand, the 'height of the floor of the back passage" varies, depending on whether the passage is carved without digging at all or by digging to the same level as the sepulcher floor or halfway. Therefore, the analysis pattern is varied by varying the back passage floor level by 1 mesh from '0 m,' which corresponds to cases without digging, to '3.6 m,' which corresponds to cases where the passage was carved out by digging to the same level as the sepulcher floor.

3 Results and Discussion

Figure 5 shows a graph indicating the maximum value of the maximum principal stress. As indicated in this graph, regardless of the position of the connecting part, the maximum value of the maximum principal stress increases slightly as the back passage is lowered and then turns to decrease, turning to increase again after reaching its minimum value. Note that the location where the maximum principal stress occurs is the roof over the front side of the connecting part (Fig. 5-A) before the maximum principal stress reaches the minimum value and the roof over its rear side (Fig. 5-B) after the maximum principal stress reaches the minimum value. The following reason is conceivable for the above change in the maximum value and the location where the maximum principal stress occurs.

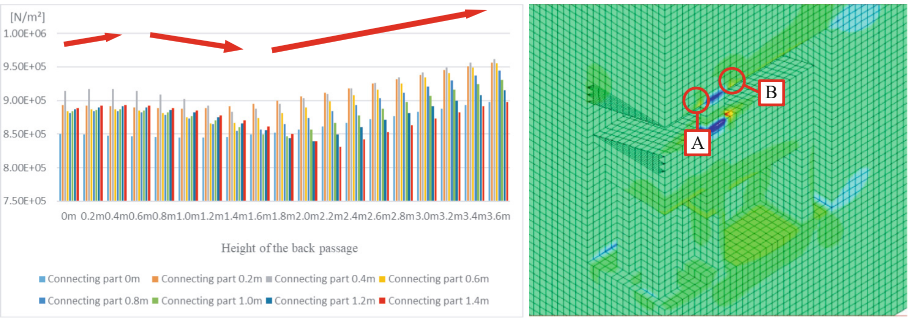

Fig. 5. The maximum value of the maximum principal stress and Location of the maximum value of the maximum principal stress. Source: Created by the Author.

According to the deformation diagram of the rock-cut tomb, before the floor of the back passage is lowered, the connecting part is tilted in such a manner that its lower end is pulled toward the rear of the rock-cut tomb (Fig. 6-A). As the floor of the back passage is lowered, the tilt decreases, and the connecting part becomes vertical (Fig. 6-B). When

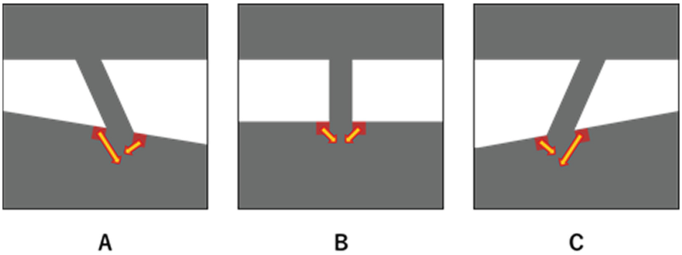

Fig. 6. A schematic diagram of deformation patterns of the connecting part. Source: Created by the Author.

the back passage is lowered further, the connecting part becomes tilted in such a manner that its lower end is pulled toward the front of the rock-cut tomb (Fig. 6-C).

In light of this, whereas the load P_1(Fig. 7) is applied to the rock-cut tomb from the rock wall over its upper part via the connecting part, since this load is displaced from the center of gravity of the rock-cut tomb (Fig. 7-X_1), the overturning moment $M_1(=P_1 \times X_1)$ (Fig. 7) is generated on the rock-cut tomb. On the other hand, a load from a rock wall behind the rock-cut tomb (Fig. 7-A) generates the diagonal load P_2 (Fig. 7) to the rear of the back wall of the rock-cut tomb via the floor of the back passage. P_3 (Fig. 7), the horizontal component of the load P_2, generates the counterclockwise overturning moment M_2 ($=P_3 \times X_2$) (Fig. 7), and P_4 (Fig. 7), its vertical component, generates M_3 ($=P_4 \times X_3$) (Fig. 7). If the floor level of the back passage is "0 m", the rock-cut tomb is caused to rotate backward since "$M_2 + M_3$" is greater than M_1. Therefore, the lower end of the connecting part is pulled backward as shown in Fig. 6-A, and an enormous maximum principal stress is generated on the roof surface anterior to the connecting part. If the floor of the back passage is lowered, as the volume of the rock wall above the floor of the back passage (Fig. 7-B) then increases, P_3 and P_4 increase, making "$M_2 + M_3$" more excellent. Therefore, the tilt of the connecting part increases, and the maximum principal stress generated in locations anterior to the connecting part becomes even greater. If the floor of the back passage is lowered further, the difference between M_1 and "$M_2 + M_3$" becomes smaller since X_2 becomes shorter even though P_3 and P_4 increase. Therefore, the rotational force toward the rear of the rock-cut tomb decreases, and the connecting part changes its direction toward the vertical direction, causing the maximum principal stress to be distributed to the roof surfaces anterior and posterior to the connecting part to reduce the maximum value of the maximum principal stress. If the floor level of the back passage falls below the center of gravity of the rock-cut tomb, as P_3 turns into a counterclockwise overturning moment, the tilt of the connecting part, in turn, comes to be determined by the balance between "$M_1 + M_2$" and M_3: if these two values become equal, the connecting part becomes completely vertical as shown in Fig. 6-B. As a result, the maximum principal stress comes to be equally distributed between the roof surfaces anterior and posterior to the connecting part, minimizing the maximum value of the maximum principal stress. Subsequently, the rock-cut tomb is caused to rotate forward as "$M_1 + M_2$" becomes greater than M_3. Therefore, the lower end of the connecting part is pulled forward as shown in Fig. 6-C to cause the maximum value of the maximum principal stress to occur on the roof posterior to the connecting part: the maximum principal stress then increases as its tilt grows greater.

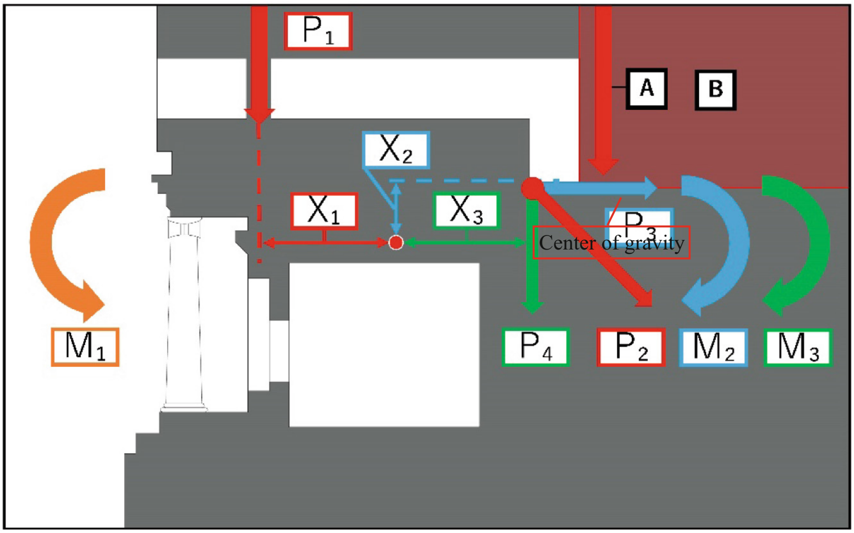

Fig. 7. A schematic diagram of the cross-section of a rock-cut tomb. Source: Created by the Author.

Incidentally, the further backwards the position of the connecting part is, the lower the floor level of the back passage is when the maximum value of the maximum principal stress is minimized (Fig. 8). This is because a larger value of M_2, hence a larger value of X_2, is required to obtain "$M_1 + M_2 = M_3$" since M_1 becomes smaller if X_1 becomes smaller.

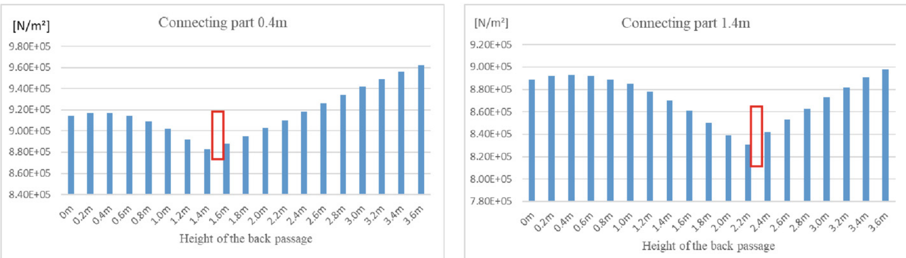

Fig. 8. Different positions at which the maximum principal stress becomes minimum. Source: Created by the Author.

4 Conclusion

The conclusion obtained by this study is summarized below.

1) As the floor level of the back passage is lowered, the maximum value of the maximum principal stress initially occurs on the roof surface over the front side of the connecting part, increases slightly, and then turns to decrease. After the maximum value of the maximum principal stress reaches its minimum value, the location where the maximum value of the maximum principal stress occurs changes to the back side, and the maximum value of the maximum principal stress starts to increase.
2) The further backward the position of the connecting part is moved, the lower the floor level of the back passage is when the maximum value of the maximum principal stress becomes minimal.

In the future, it is intended to analyze, among others, the influence of differences in aspects of a rock-cut tomb other than its connecting part and back passage, for instance, differences in the shape of its roof and its side passage, on its structural characteristics. It is intended to evaluate the structural reasonability of actual rock-cut tombs at the stage where the influences of differences in each part of a rock-cut tomb on its structural characteristics are grasped.

Reference and Notes

1. Fedak, J.: Momumental Tombs of the Hellenistic Age, p.3, Toronto (1990). In this book, Fedak summarizes information on tombs of the Hellenistic age hitherto reported and describes their characteristics. Fedak therein cites the possession of multifarious architectural forms as one of the characteristics of tombs of the Hellenistic age
2. Akisumi, T.: A study of the regional and historical trait of built tombs from the view point of use of the column: A study of the regional and historical trait of Hellenistic tombs (1), Journal of the Architectural Institute of Japan, Planning systems, No. 597, pp. 189–195 (2005). Akisumi, T.: A study of the regional and historical trait of built tombs from the view point of the burial position and use of the podium: A study of the regional and historical trait of Hellenistic tombs (2), Journal of the Architectural Institute of Japan, Planning systems, No. 611, pp. 219–224 (2007). Akisumi, T.: Design method of the lion tomb at amphipolis: Design methods of Hellenistic tombs (1), Journal of the Architectural Institute of Japan, Planning systems, No. 613, pp. 235–241 (2007). Akisumi, T.: Planning method of the nereid monument at xanthos: design methods of Hellenistic tombs (2), Journal of the Architectural Institute of Japan, Planning systems, No. 627, pp. 1105–1112 (2008). Akisumi, T., The Architectural Elevation Planning Method of the Nereid Monument at Xanthos Design methods of Hellenistic tombs (3), Journal of the Architectural Institute of Japan, Planning systems, No. 658, pp. 2961–2967 (2010). Akisumi, T., Characteristics of the Facades of Rock-Cut Tombs in Southeast Caria that Imitate Ancient Greek Temples, Journal of the Architectural Institute of Japan, Planning systems, No. 695, pp. 217–226 (2014)
3. It is one of morphological categories of toms of the Hellenistic age and refers to tombs built by excavating rock walls. There are two types of rock-cut tombs: tombs of the stand-alone type built by separating them from surrounding rock walls and tombs of the facade type built by directly constructing the facade of a tomb without separating it from rock walls

4. Caria is an area in the present southwestern part of Turkey. Caunus is one of ancient cities located in Caria
5. Roos, P.: Survey of Rock Chamber-Tombs in Caria, Part 2 Central Caria, Goteborg (2006). Roos, P.: Survey of Rock Chamber-Tombs in Caria, Part 1 South-Eastern Caria and the Lyco-Carian Borderland, Goteborg (1985). Roos, P.: The Rock Tombs of Caunus, Goteborg (1972)