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RESEARCH ARTICLE

Structural performance of authentic architectural heritage designs: A masonry monument in Western Anatolia

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Abstract The aim of the study is to present a multi-leveled comparative evaluation approach for structural characteristics of historic masonry monuments so that the consciousness in their authentic designs is comprehended, and the optimum structural performance is clarified. A case study approach is preferred by the examination of the *Bedesten* (15th–16th centuries) located in Bergama, İzmir, Turkey. The structure is documented through tacheometric techniques. The construction techniques of structural elements are mapped. These documented qualities are compared with similar period and/or function structures in order to rank the frequency of construction details. The geometrical factor of safety state is defined theoretically for domes and arches. Finite element macro model of the *Bedesten* is generated in ANSYS software and overall structural analysis of the structure is made to evaluate the safety level of historic building by the limit states through self-weight analysis. The presented study shows that the rare structural characteristics can both contribute to structural safety and cause vulnerability. Therefore, total consciousness in structural design cannot be stated for the studied *Bedesten*, but the structural designs that are often preferred in the monuments built at the same period in the proximity to each other have low vulnerability, yielding to conscious preferences.

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1. Introduction

Historic structural systems and construction techniques used in monumental masonry buildings are the product of experience over centuries. Although the continuing developments in the techniques gained through experiences are expected to contribute to the enhancement of structural qualities, the sustaining of construction traditions may sometimes lead to the vulnerability of the structural systems. To assess the contribution of construction techniques to the structural behavior, firstly the identification of used techniques and materials should be made. There are different studies explaining the construction techniques and materials of a chosen structural element type, classifying the structural elements of a building and documenting the construction techniques for each element or studying structures with their construction techniques for a certain period or geography.

Within the examined literature, the studies defining construction techniques for a structural element type focused on masonry walls, arches, vaults and domes. For the walls, Batur (1970) carried out a study documenting wall construction technique with an alternating order in Ottoman mosques built between the 14th and 18th centuries. The most common period for this technique was determined as the 14th–15th centuries. Among examples dating to the first half of the 15th century, the use of brick and stone materials in 1/1 order is seen. This order expresses one stone and one brick placement side by side on horizontal directionality, while one row of brick and one row of stone lay exist in vertical order. This study gives a detailed knowledge about the lay orders of walls in elevation view. However, the sectional order qualities are not documented. Kutlu (2017) also examined the alternating wall order in the 14th–15th century Ottoman Period mosques. The study defines the material lay orders as vertical alternating order without the use of vertical brick placement between the stones or composite lay orders which display both horizontal and vertical brick usage between the stones. The study revealed that the cut stone usage in this order did not occur directly in the 16th century but in the 15th century the technique started to be used. The work gives schematic representational elevation drawings that shows the main classification orders in elevation view but the sectional qualities again are not represented. Anzani et al. (2018) tried to understand the historical masonry techniques for conservation. The masonry walls were classified according to the section quality of their construction techniques as one-single leaf, two leaves well interlocked (with transverse connecting stone), two leaves partially interlocked, two leaves not interlocked and three leaves or multiple leaves. Although it gives the section layout of masonry material, the elevation view is not presented. Apak (2019) explained the wall construction technology of Ottoman Period by several case study baths accommodating varying use of masonry materials as cut stone, rubble stone, etc. The use of tie beams, and sectional qualities as three or single-leaf construction are the expressed qualities for the wall designs. Instead of detail drawings, only photographic representation is preferred for the wall masonry patterns.

Batur (1973) defined the structure and geometry relationship of the arch designs in Ottoman Mosques built between 1300 and 1730. The arch is expressed as the constitutive element of Ottoman period structures. The arches within the mosque designs are classified as structural arches and decorative arches. Yavuz (1983) documented and classified vault and arch profiles belonging to Anatolian Seljuk Period structures. The geometrical shape of the profiles became effective for the naming of the arch and vault types. These studies provide knowledge about the profile types for the related superstructure elements. However, the representation of construction technique for the lay of masonry material within the components are not presented in plan, section or elevation views. Vidal (2017) examined the evolution of construction techniques in the Early Gothic by giving special attention to the sexpartite vaults. A comparative study was carried out to identify the construction detail differences for this special type of vault in varying European countries. Armi (2004) investigated the use of pointed arch profile in Romanesque period architecture. The constitutive role of this structural profile in groin vault design is also emphasized with the used construction details. Reyhan et al. (2013) examined the construction techniques of domes in a group of Ottoman baths. The layout of bricks in section view and stacking order of masonry material in elevation are represented in drawings for the different styles observed within selected examples creating a comparison opportunity.

The example studies classifying the structural elements of a building group create sources for the comparison of construction techniques used in a building type. Reyhan (2004) examined the construction techniques and materials of Ottoman period baths dating to the 15th–16th centuries in the Seferihisar-Urla region. The structural systems and lighting systems are examined, while knowledge about the installation system is also provided. The construction techniques of the structural system are listed for walls, transition elements, superstructure and floors. The representation and comparison of construction techniques were carried out mainly through photos, although for the distinctive designs some detailed drawings were produced. For the wall types, plan, section and elevation detail drawings were presented, too. Matracchi et al. (2021) tried to define the construction techniques and concepts used in the cathedrals of Pisa, Siena and Florence. In addition to the authentic constructive aspects, the structural adaptations following the earthquakes, the solution details for structural instability during the construction of the large vaults in Florence Cathedral were expressed.

Defining general construction techniques used in traditional Anatolian architecture constitutes the last classification style. In this approach, Aktuğ (1989) defined the construction techniques used in the 14th century Principalities architecture in Western Anatolia. The study focuses on the construction techniques and materials used in different building components: wall, column, column head, pillar, arch, transition element and superstructure. For each structural element type, the example construction technique details from different building types are presented by different views as 3D section, elevation or ceiling plan views to define the general construction techniques used in a certain period. Tayla (2007) classified structural systems and elements of traditional Turkish architecture according to their material types. After the general identifications for the building types and local material types, traditional foundation and wall systems are examined in detail. Walls are classified under rubble stone, rough-cut stone, cut stone masonry, with an alternating order, wooden, wood carcass, mud-brick, and brick subheadings. Wall orders were identified in elevation views for a variety of case study structures.

Although the existence of different approaches for the examination of construction techniques and material usage in historic masonry buildings, an evaluation strategy including all the construction details belonging to each structural component of a selected monumental building and comparing its structural characteristics with similar building types or the buildings that display some similarities for a number of structural element types is not present. The relation between the selected construction techniques to the structural vulnerability or safety of the monumental buildings is also not examined in these studies. The structural theory of masonry defined by Heyman (1995) considering different structural components of historic monumental buildings such as domes, vaults and arches, can be helpful to understand the stress distribution principles in the structural components and to learn the minimum dimensions for safe design of structural elements according to the geometrical factor of safety. It is a beneficial approach for the control of the structural design of historic monumental masonry buildings to decipher the validation state with the theory. Lopez-Manzaneres (2023) reviews the literature focusing on the structural limit analysis of masonry domes in the 18th century. The kinematic collapse mechanisms and static equilibrium states for domes defined through the theories are listed together with the examined structure. The contribution of Heyman in the 20th century for the structural theory of masonry encompasses a wider context including different structural element types providing the overall safety design identification for masonry structures.

The computer-aided numerical modeling softwares can also give the opportunity to assess the structural behavior and stress states under the self-weight of the structures which can be used to validate both the suggested theory by Heyman, and to detect safe and risky portions of the masonry buildings under their dead load. In general, numerical structural assessment analyses are carried out to detect the vulnerable spots of the masonry structures under seismic loading without creating relations with the special construction techniques used in heritage buildings. However, the self-weight analysis which is carried out as a previous step in these seismic loading behavior determination studies is also important to reveal the weak zones of the structure without any loading rather than its self-weight which will prove the construction technique contribution to structural safety or vulnerability. For example, Aghabeigi et al. (2021) carried out static analysis under dead load and examined the principal stress distribution of a historic masonry building. There is no attempt to create relation with construction technique and analysis results. There are limited studies focusing on the effect of construction techniques to the structural behavior. Gençer et al. (2020) examine the bonding techniques of ancient dry masonry tower walls located in Caria, Pamphylia and Cilicia regions. The effect of the variety in the bonding qualities on the structural behavior is determined through discrete element models allowing to show the failure mechanisms of the masonry blocks. Since, towers have limited structural component type as only wall, the study focuses on the masonry block failures in detail by discrete element method which aims to model each masonry stone material separately. However, for the structures that have multiple structural element and material types—domes, arches, transition elements, pillars, walls, etc.—built with brick masonry or stone masonry including mortar, discrete element method can be hard to apply. Thus, finite element method allowing the macro modeling which admits the masonry as a composite of mortar and brick/stone becomes useful to represent and assess the structural behavior. In this approach, rather than the bonding order, the volumetric qualities (thickness, span, etc.) determine the safety state of the structure.

The aim of the study is to present a multi-leveled comparative evaluation approach for structural systems in historic masonry monuments so that the consciousness in their authentic designs is comprehended; and the optimum structural performance is clarified. A case study approach is undertaken: The *Bedesten* (15th–16th century) in the historic center of Bergama in Western Anatolia is focused on. The objectives are to identify the architectural qualities with emphasis on structural elements, construction techniques and material usage in the selected monument, to compare these qualities with those of similar period and/or function buildings, to make structural analysis of the selected monument and to evaluate the performance of its structural elements with respect to the frequency of their construction.

The study carries the importance to be a guide for evaluating the extent of historic structural knowledge, and the consciousness level of the local craftsmen in benefitting from the know-how of their period by the examination of construction techniques according to Heyman's structural theory of masonry and assessment of the construction technique contribution to structural safety or vulnerability by numerical analysis.

2. Materials and methods

The methodology combines the tools of architectural conservation and civil engineering. First, tacheometric survey and visual analysis of the *Bedesten*; literature review and archive research on the case study and similar period buildings were realized to direct comparative studies for spatial qualities and construction techniques. Bergama *Bedesten* is preferred as the case study since it has not been restored so far and authentic constructional details can be observed (Fig. 1). Next, the compatible and contradictory aspects of the structural design of the *Bedesten* with the Heyman's structural theory of masonry were evaluated for the arch and dome components. Their validation by the application of self-weight analysis benefiting from finite element method was realized, as well. The numerical analysis also allowed to evaluate overall

Fig. 1 Case study: Bergama *Bedesten*. Source: The Authors.

structural performance of the building under its self-weight and the detection of the safety state for other rare qualities in the structure in addition to arch and dome designs.

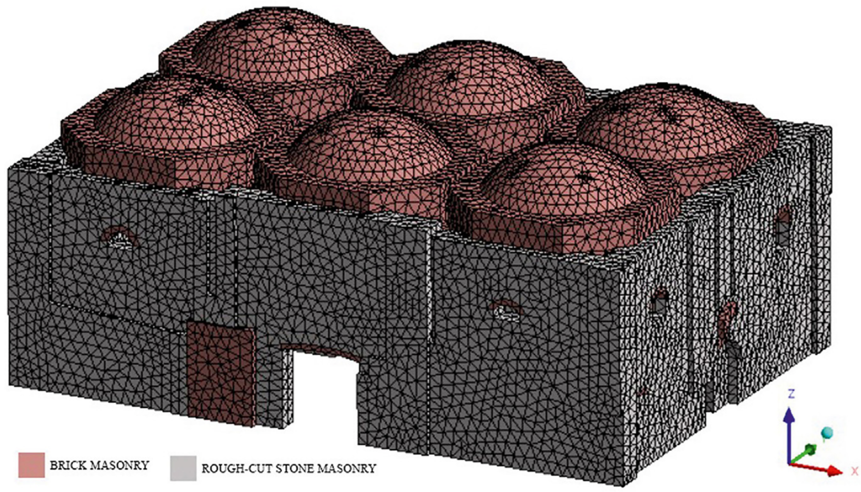
By the use of tacheometric survey knowledge, the scaled drawings of the building and construction details of each structural element were prepared in Autocad software. Visual analysis of the spanning elements, transition elements, vertical elements, floor and architectural elements was made on measured survey drawings. Then, the construction techniques and material usage were illustrated on detail drawings: partial plan, section and elevation. The architectural significance of the case study was evaluated by comparing its spatial qualities with other *bedesten*s with similar spatial organization and scale in the other Ottoman cities of the period. Then, its structural qualities were compared with those of the same period masonry monuments in the same region and *bedesten*s in other cities presenting similarities in terms of construction manners. The dimensions of the structural elements of comparative examples were derived from the scaled drawings available in the archives or literature. The frequency of construction of each element and technique used in the Bergama *Bedesten* was ranked as rare or common. The following map shows locations of the buildings for comparative studies of spatial qualities and construction technique and material usage qualities (Fig. 2).

The structural elements detected in Bergama *Bedesten* were evaluated according to the structural theory of masonry (Heyman, 1995). The limit dimensions suggested in the theory for the safety of the structure were evaluated. Then, the self-weight analysis displaying the maximum principal stress values under the dead load of the structure was carried out. This application allowed to reveal the zones that are exceeding the limit tensile strength values of the materials. So, at this phase, the previous construction technique and material usage analysis knowledge was also used. The macro model of the Bergama *Bedesten* was generated in ANSYS software benefiting from the finite element method. The rough-cut stone masonry and brick masonry material parameters were selected from the Guideline for Management of Earthquake Risks for Historical Buildings to be used in macro model (Republic of Turkey General Directorate of Foundations, 2017) (Fig. 3). Tensile strength value is taken as 10% of the compressive strength values of the material types (Koçak, 1999). After tetrahedrons mesh design with 0.4 m average sizing, the static structural analysis was realized to derive maximum principal stress in the structural components under standard earth gravity and dead loads. The associations with the construction techniques used in the structure and the self-weight analysis results were made.

3. *Bedesten* as a building type

*Bedesten*s were the places where valuable gems, as well as weapons, harnesses and precious fabrics were sold (Eyice, 1992; Ortaylı, 2020). The safes, documents, notebooks of

Fig. 2 The locations of the buildings selected for comparative studies. Source: Revised from Google Earth (2023).



Wall Type	Compressive Strength f_m (MPa)	Shear Strength T_0 (kPa)	Modulus of Elasticity E (MPa)	Shear Modulus G (MPa)	Unit Weight w (kN/m^3)
Rough cut stone masonry wall	1.1	35	1020	170	20
Brick masonry wall with lime mortar	1.8	60	1800	300	18

Fig. 3 Macro model of Bergama *Bedesten* with assigned material parameters. Source: The Authors.

the shopkeepers and merchants, and the documents of the tradesmen and craftsman guilds were kept in here as well (Özdeş, 1953; Eyice, 1992). They were similar to today's modern bank and stock exchange (İnalcık, 1980). Bedestens were built as waqf foundations (İnan, 1996).

The emergence of *bedesten* as the focal element of the commercial centre of Ottoman cities took place in the Ottoman Period (Cezar, 1985; Eyice, 1992*)*. The first *bedesten* was built in Bursa by Bayezid I towards the end of the 14th century. Bursa *Bedeste*n scheme covered with domes and surrounded by vaulted shops became a typologic example for later *bedesten*s with small changes (Kuban, 2007). They were mostly constructed in the 15th and 16th centuries. In each city, there was only one *bedesten* in general.

Shops surrounded the facades of the *bedesten*. When shops were organized on either side of a covered or an open air street, they could be used by a group of merchants specialized in various arts and crafts, e.g., shoemakers' *arasta*, slippers' *arasta*, fürriers' *arasta*. The height of the shops may reach the half of the height of the *bedesten* walls, e.g., the Amasya *Bedesten*, Edirne *Bedesten*, Tire *Bedesten*.

Eyice (1992) emphasizes the blindness of the *bedesten* walls and states that there were a few top windows. These top windows had iron shutters. There were rarely oculi for lighting and ventilation in the domes. They generally had four entrances and sometimes three. *Bedesten*s were square or rectangular in plan, e.g., Galata *Bedesten* and Bursa *Bedesten*. The interior was organized as a total space. There could be small units along the sides. These small units were called as "*mahzen*". They were used as storage spaces. Amasya *Bedesten*, Serez *Bedesten* and Gelibolu *Bedesten* are examples for total space organization without *mahzen*s. Bursa *Bedesten*, Edirne *Bedesten* and Tire *Bedesten* can be given as examples for *bedesten*s with *mahzen*s (Ayverdi et al., 1976).

4. Results

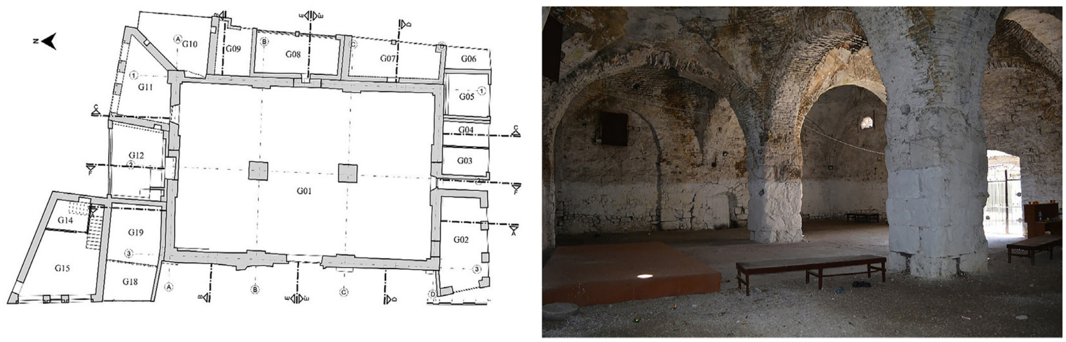
The context, spatial characteristics, facades, and construction techniques and material usage of the case study; its place among similar examples by spatial qualities; and the frequency of its construction technique qualities are presented.

4.1. Context, spatial organisation and facades

Bergama *Bedesten* is a listed heritage within the urban archaeological site of Bergama, İzmir. It is the focal place in the historic trade center. Within its close-by environment, there are other monumental buildings, khans, masjids, mosques, etc. (Fig. 4).

Bergama *Bedesten* is composed of one monumental hall and lately-added small shops surrounding its facades. There are no adjacent shops flanking its west facade because they were demolished. All of the shops were built after the demolishment of the authentic vaulted shops surrounding the *bedesten* up to half height. The hall (21.2 m × 14 m) of *Bedesten* is numbered as G01 (Fig. 5). It is rectangular in plan with two galleries defined by two central piers (1.46 m × 1.53 m and 1.47 m × 1.57 m). Three domes are present in each of the two galleries. Their heights vary between 9.7 m and 9.8 m. Each rests on plane triangles and then arches. The heights of the arches vary between 5.7 m and 5.9 m. With these dimensions, the hall area has a monumental scale.

Fig. 4 The Bergama *Bedesten* as viewed from the north-west (a), south-west (b), south-east (c) and north-east (d), site plan (middle). Source: The Authors.



(a) (b)

Fig. 5 Ground floor plan (a) and interior view (b) of Bergama *Bedesten*. Source: The Authors.

The west facade of Bergama *Bedesten* is crowned by three domes finished with over and under tiles. It gives the impression of a solid element except the central entrance opening and two top windows on its sides. The top windows are partially infilled. There are projections on the *bedesten* wall coinciding with the arches that the domes are carried by. Some of them were damaged and infilled at their bottom levels with brick or stone material. At the northern bottom part, the traces of vaults can be seen. There is a single-storey restaurant with Neoclassical facade elements towards its southern part and there are two masses towards its northern part (Fig. 6).

The north facade is crowned by two domes finished with over and under tiles. It is hardly visible because of the commercial buildings flanking it. Its bottom portion is totally surrounded by shops. The mass addition in the middle is located in front of the northern entrance door of *bedesten* which is also filled in at present. There are two top windows on the northern facade of *bedesten*, but they cannot be observed at outside because they remain under the roof level of adjacent shop masses. The projections at *bedesten* walls are located at the corners and in the center (Fig. 7).

The east facade is crowned by three domes finished with over and under tiles. It is divided into three portions by the projections coinciding with the arches at the interior. Each portion has top windows: one at each side and two at the center. Its bottom level is surrounded by shops. The shop mass which is in the middle is in front of the eastern entrance door of *bedesten* hall which is also infilled like the one in north side (Fig. 8).

The south facade is crowned by two domes finished with over and under tiles. Only one of the two top windows observed at the interior is visible from the exterior facade. The original southern entrance door of *bedesten* hall is partially visible through the gap between the surrounding shops. It has an iron rectangular door with cut stone frame within the infill material of authentic arched door opening. The single storey commercial units hide the bottom level of the monument. The projections at *bedesten* wall are located at the corners and in the center (Fig. 9).

4.2. Construction techniques and material usage of Bergama *Bedesten*

The construction techniques used in Bergama *Bedesten* are analyzed in the order of spanning elements, transition elements, vertical elements, floor and architectural elements. Materials of structural and architectural elements are expressed for each structural or architectural element type.

4.2.1. Spanning elements

Arches have double centers with different levels in current situation. In original form, they should be pointed arches with double centers which is common in 15th–16th centuries (Batur, 1973). Irregular placement of centers is the clue of

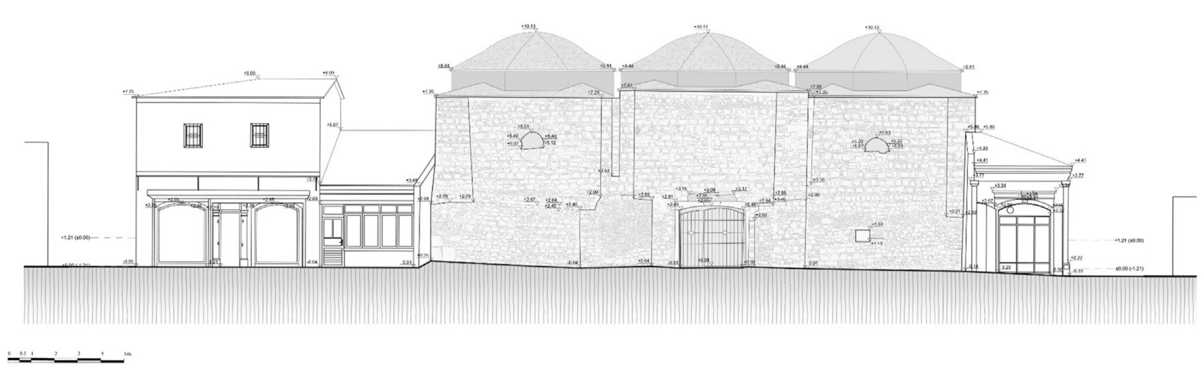


Fig. 6 West elevation of Bergama *Bedesten*. Source: The Authors.

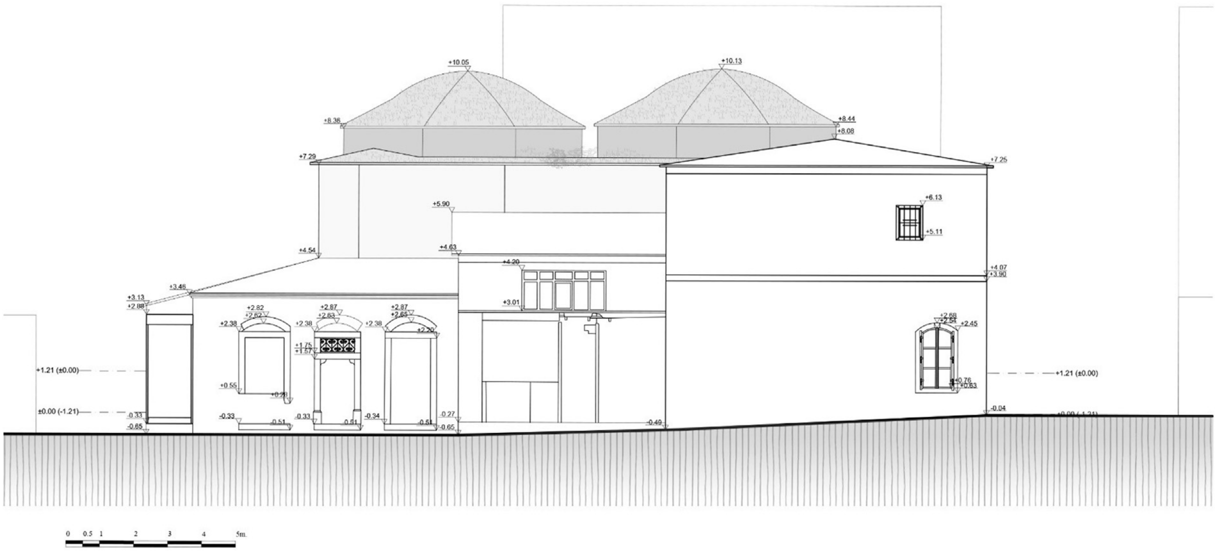


Fig. 7 North elevation of Bergama *Bedesten*. Source: The Authors.

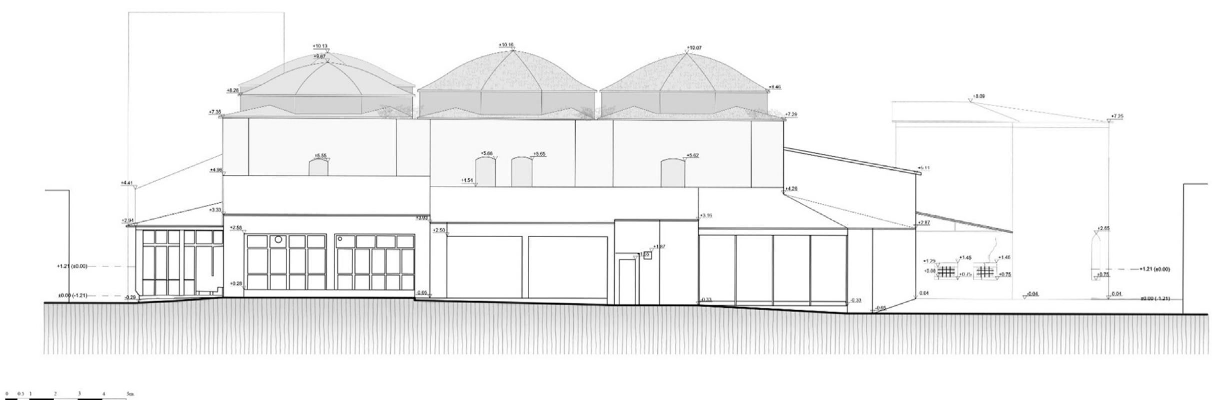


Fig. 8 East elevation of Bergama *Bedesten*. Source: The Authors.

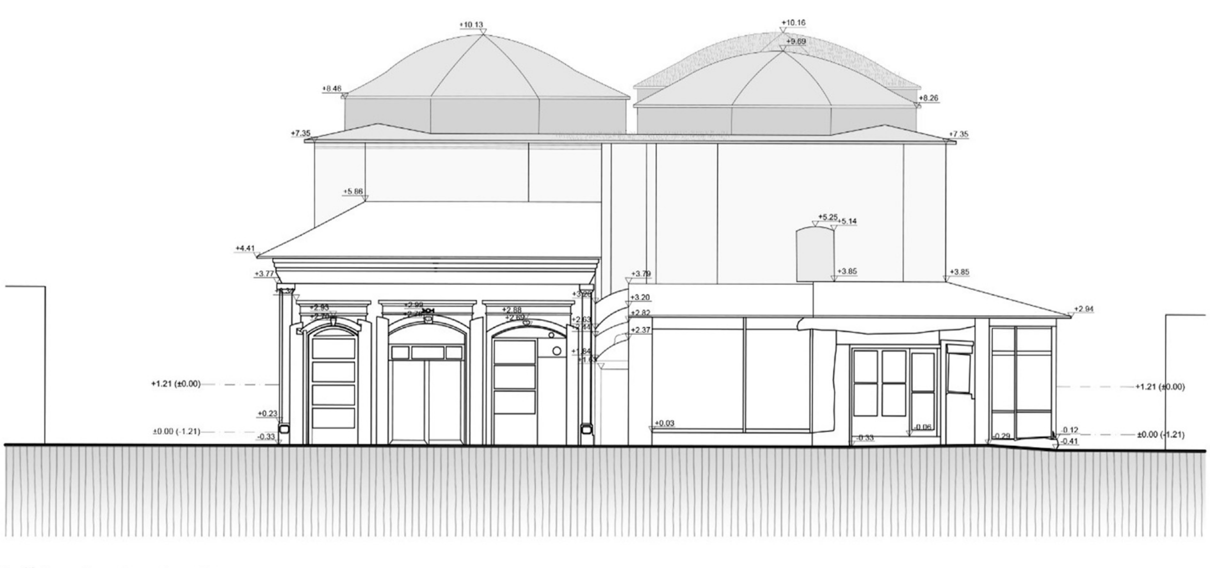


Fig. 9 South elevation of Bergama *Bedesten*. Source: The Authors.

displacement. They are out of brick ($20-35 \times 5 \times 27\,cm^3$) and mortar (5 cm in thickness). The thickness of their voussoirs is 27 cm. They are grouped into three types according to their spanning distances and their placement within the structure.

The first type has the span varying between 5.75 m and 6.15 m. Its rise also varies between 2 m and 2.50 m. These arches, of which are six, are parts of the wall construction and can be observabled from inside. The second type arches are also parts of the wall system. They are four in number and observed in north and south facade walls at two sides of the main entrance doors. This type has the span varying between 4.20 m and 4.30 m. They are narrower than the first type in order to provide space for the door openings in the center of northern and southern facades. Their rises vary between 1.45 m and 1.55 m. The third type has the span varying between 5.95 m and 6.05 m. These arches, of which are seven, are between facade walls and pillars. Their rises vary between 2.50 m and 2.75 m.

The crown thickness for the first two types is assumed as 35 cm. which is the thickness of a single brick unit. This thickness for the third type is 1.12 m. Here, three or four brick units are laid side by side to form the arch profile. Some arches are covered with both plaster and white wash, while some of them have only white wash.

Domes are six in number and have two-centered depressed profiles. In this profile type, the central height is higher than the dome height. The half distance of span is smaller than the arc radius (Reyhan, 2011). They are constructed with brick and have the thickness of 35 cm. So, one brick unit ($35 \times 20-27 \times 5\ cm^3$) creates the depth of a dome. Their span varies between 6 m and 6.30 m. Their rise varies between 2.35 m and 2.85 m. The mortar thickness between brick materials is 5 cm, which is equal to the thickness of brick (Fig. 9).

4.2.2. Transition elements

Transition elements are classified as plane triangle, drum and profile. In order to transit from a square plan to an octagonal drum, plane triangles could be used in the 14th century during Principalities period (Aktuğ, 1989). Although Bergama *Bedesten* was built in 15th–16th centuries, it has plane triangles. Their height varies between 1.10 m and 1.82 m in the structure. The dimensions of the brick units are $35 \times 20-27 \times 5\ cm^3$. They are stacked one above another creating an inclined surface. Mortar thickness between brick units varies between 2 cm and 5 cm.

Octagonal drums surround the domes from outside creating resistance to outward thrust in domes. They are built with andesite rough-cut stone and brick in alternating order. Their heights are nearly 1 m.

They are the octagonal planned bases of the domes at the interior without any curvature and with heights of approximately 55 cm. The profiles create transition from plane triangles and walls to the dome curve. They are constructed out of brick units and mortar 5 cm in thickness (Fig. 10).

4.2.3. Vertical elements

Vertical elements are classified as walls and pillars. There are five different wall types. The wall type 1 thickens at bottom level. In the upper level, wall thickness is 78 cm, while in the bottom level, the thickness is 92 cm. Its construction technique is three leaf masonry. The core part has rubble stones and bricks in pieces. The leaves of both inner and outer faces are built with only andesite rough cut stone in the bottom portions, and rough cut stone alternating with brick in top portions. This alternating order of materials is called as *"almaşık"*. Batur (1970) presents Ottoman mosques in which this construction technique is used in Marmara region between 14th and 18th centuries. Different types of this special wall system were created by the usage of different materials, same material with different dimensions or same material with color difference. The most common materials are brick and stone for the first type which is called as *opus mixtum* and had its earliest example in A.C. 31: Circus of Maxentius in Rome (Batur, 1970). Mortar varying between 2 cm and 5 cm thickness is observed between the pieces of stones and bricks in Bergama *Bedesten*.

The wall type 2 is the most common wall type in the building. Its thickness varies between 72 cm and 80 cm. Its construction technique is also three leaf masonry. The core part has rubble stones and bricks. Both inner and outer face leaves are built with andesite rough cut stone alternating with brick. Mortar varying between 2 cm and 5 cm is observed between the stones and bricks.

The wall type 3 is seen in north and south entrance doors. At these parts, the wall is thickened both inwards and outwards. Its total thickness is 120 cm. Arches carrying the domes rest above the entrance door arches and the thickening of the wall around the doors increase the resistance of the walls against the loads coming from the arches.

The wall type 4 is observed at the parts where arches integrate with the walls. So, the loads transferred with the arches are resisted by the thickened portions of the walls, which recall the piers of the building. Their thicknesses are around 138 cm.

The wall type 5 is an altered version of the wall type 4. One of the walls is demolished at the bottom projected part in the western facade. This demolished part is filled with a brick masonry wall as a later addition. The core part has rubble stones and bricks. Both inner and outer face leaves are built with andesite rough cut stone alternating with brick in upper parts. In the bottom part, masonry wall built with only andesite rough cut stone is observed. Mortar varying between 2 cm and 5 cm is seen between the stones and bricks. All wall types are covered with white wash at inner face.

There are two pillars in the central north-south axis of the building. They bear the loads of the spanning elements: domes and arches. One of them has the dimensions of 153 cm $\times$ 146 cm and the dimensions of the other one are 156 cm $\times$ 147 cm. They are built with andesite rough cut stone and mortar with varying thicknesses: between 2 cm and 5 cm (Fig. 11).

4.2.4. Floor

The floor system is identified as floor on ground. The covering material presents variation in different parts of the floor. At the interior, the northern part (level: ±0.00 m) is covered with pebbles, while the southern part is screed covering (level: $+0.05$ m). In front of the western facade,

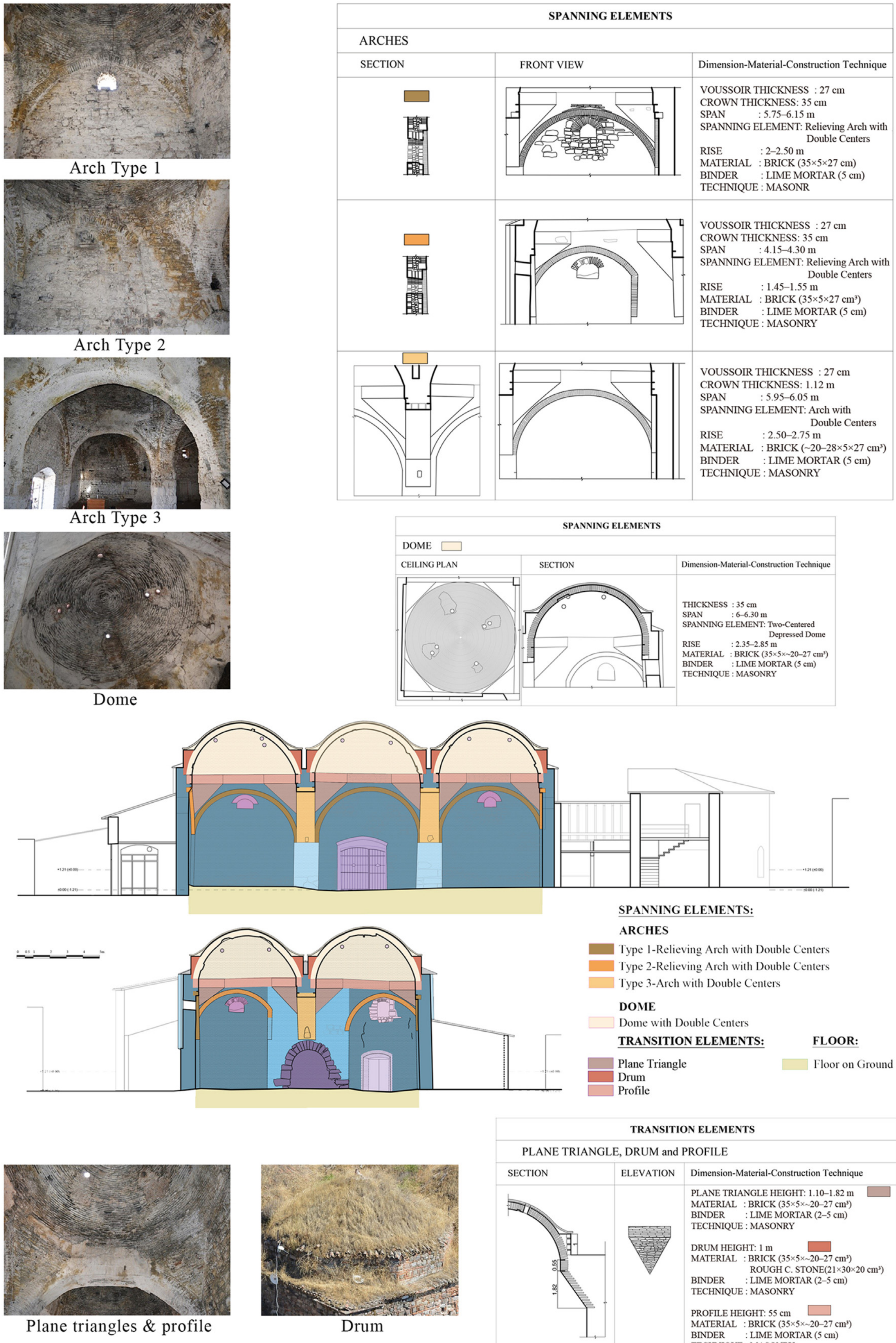


Fig. 10 Spanning and transition elements of Bergama *Bedesten*. Source: The Authors.

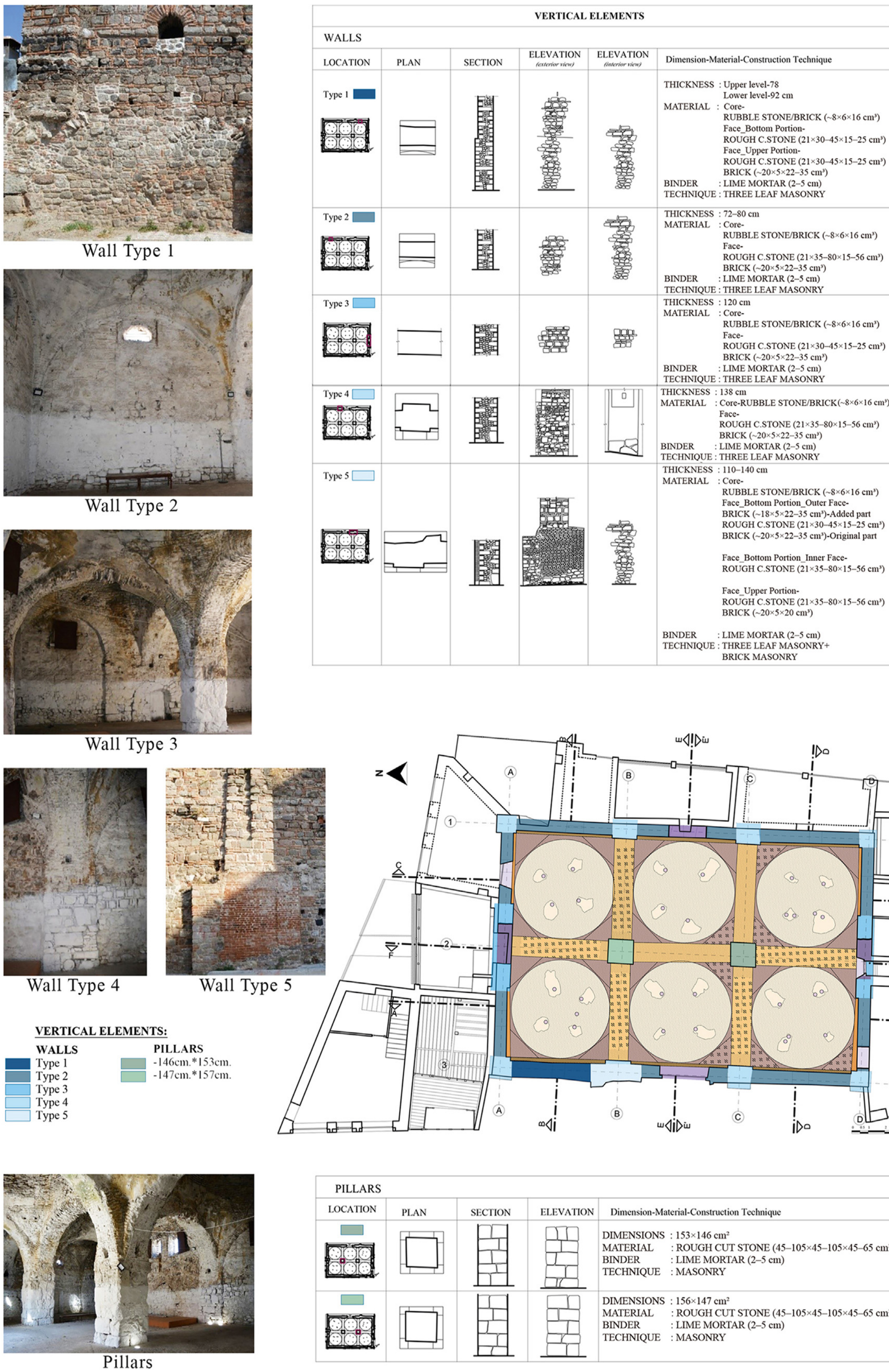


Fig. 11 Vertical elements of Bergama *Bedesten*. Source: The Authors.

there are different covering materials at the exterior. Cut stone remains can be observed at the floor part leading to the existing open entrance door. In their north, there is a partial screed covering. Cobble stones are seen at south of these cut stone coverings. There are ceramic tile covering and a part without any covering material which is expressed as earth in the analysis.

4.2.5. Architectural elements

Architectural elements are classified as main entrance doors, secondary doors, top windows and oculi.

There are four main entrance doors at the four facades of the *bedesten*. Two of them have semicircular arch, one of them has pointed arch and one of them has segmental arch. One of the doors with semicircular arch is in the center of north facade. It has the arch span of 2.20 m and arch rise of 1.25 m. Its wall and arch parts are built with andesite rough cut stone. The voussoir thickness of its arch is 60 cm. Mortar thickness is 2—3 cm. The other door with semicircular arch is in the center of south facade. It has the arch span of 2.40 m and arch rise of 1.15 m. Its wall and arch parts are built with andesite rough cut stone. The voussoir thickness of arch is 55 cm. Mortar thickness is 2—3 cm. The door with pointed arch is in the center of east facade. It has the arch span of 2.30 m and arch rise of 1.18 m. Its wall part is built with andesite rough cut stone.

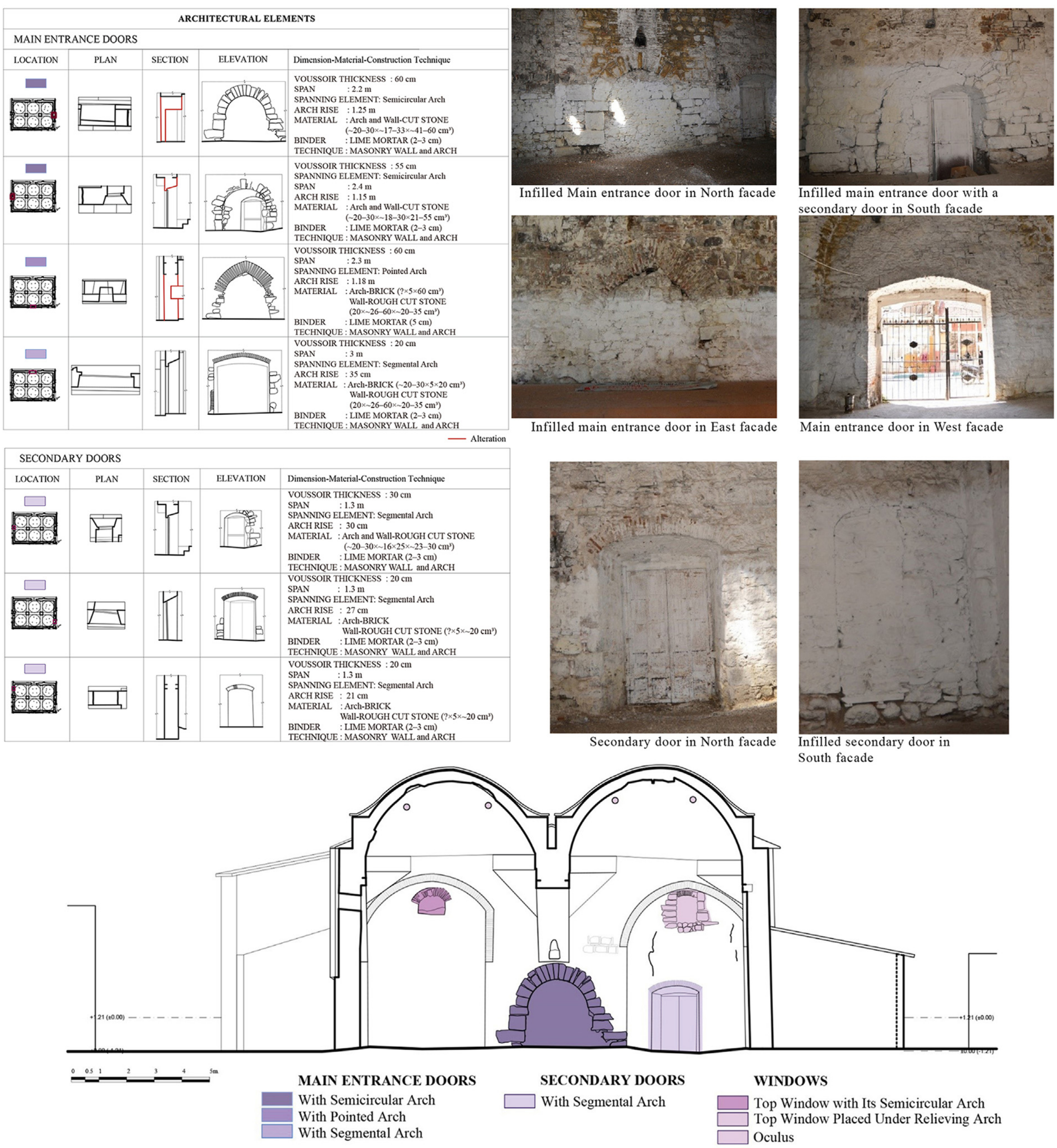


Fig. 12 Architectural elements of Bergama *Bedesten*. Source: The Authors.

Its arch part is built with brick material. Its voussoir thickness is 60 cm. Mortar thickness is 5 cm. The door with segmental arch is in the middle of west facade. It has the arch span of 3 m and arch rise of 35 cm. Its wall part is built with andesite rough cut stone. Mortar thickness between rough cut stones varies between 2 cm and 3 cm. Its arch part is built with brick material. Its voussoir thickness is 20 cm. Mortar thickness is 5 cm in arch part. 74 cm crown thickness of the arch part is gained by the lay of brick rows side by side through the profile. They are white washed on their interior surfaces.

There are three secondary doors with segmental arches in building. One of them has infill. The first one is in the south facade. It was placed under the arch of the main entrance door which had been filled in with rough cut stones. So, this door opening was formed within the previous infill. Its arch and wall parts were built with rough cut stone. It has the arch span of 1.3 m and arch rise of 30 cm. Its voussoir thickness is 20 cm. The mortar thickness varies between 2 cm and 3 cm. The second one is placed at the eastern side of main entrance door in the northern facade. Its wall part is built with rough cut stone. The mortar thickness varies between 2 cm and 3 cm at the wall part. Its arch part is built with brick and has the span of 1.3 m while the rise is 27 cm. Its voussoir thickness is 20 cm. 75 cm crown thickness of arch part is gained by the lay of brick rows side by side through the profile. Mortar thickness is 5 cm in the arch part. The third secondary door with segmental arch is at the western side of main entrance door in the southern facade. It has rough cut stone infill material in current condition. Its wall part is also out of rough cut stone while the arch part is out of brick. The mortar

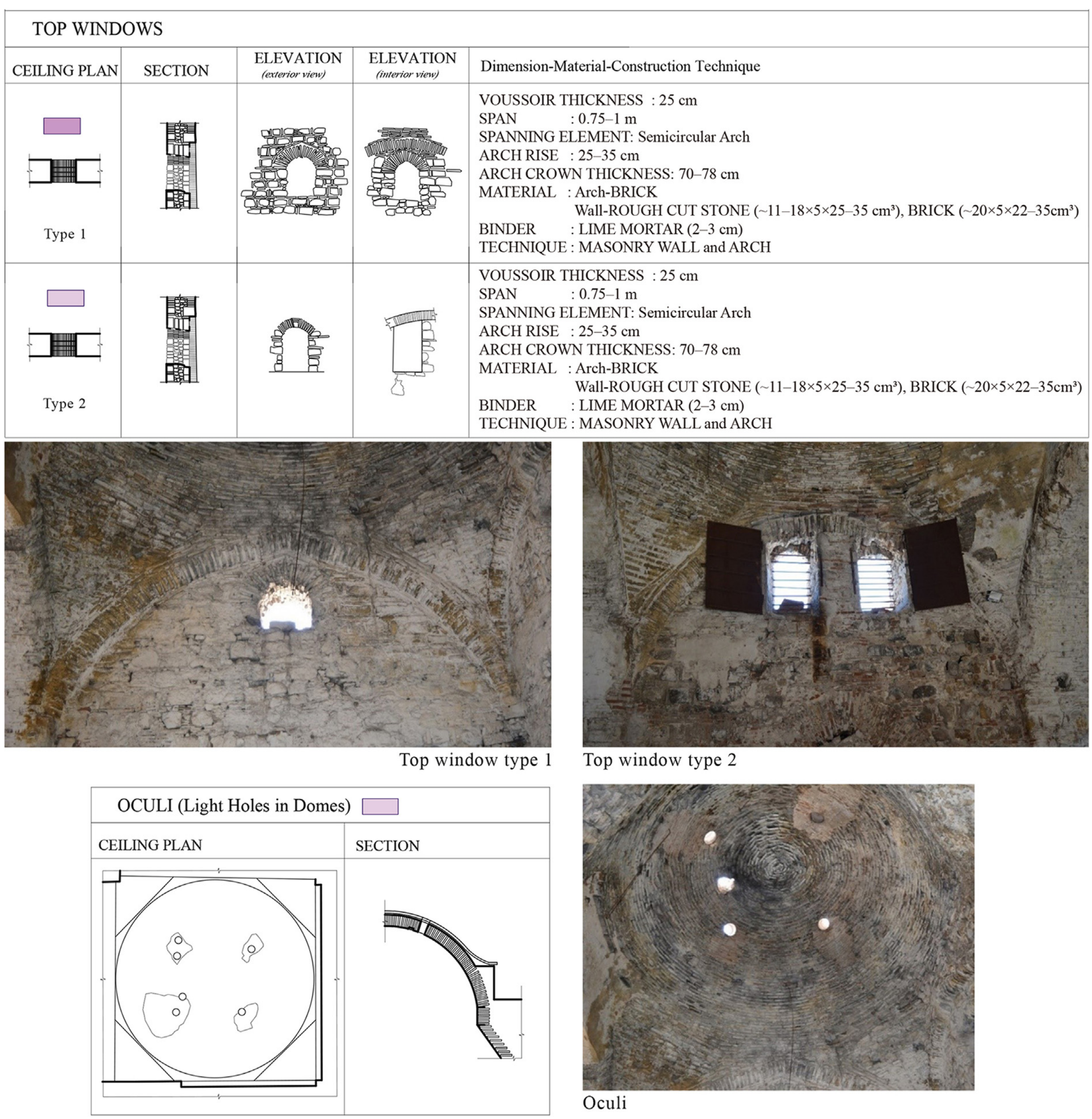


Fig. 13 Window types of Bergama *Bedesten*. Source: The Authors.

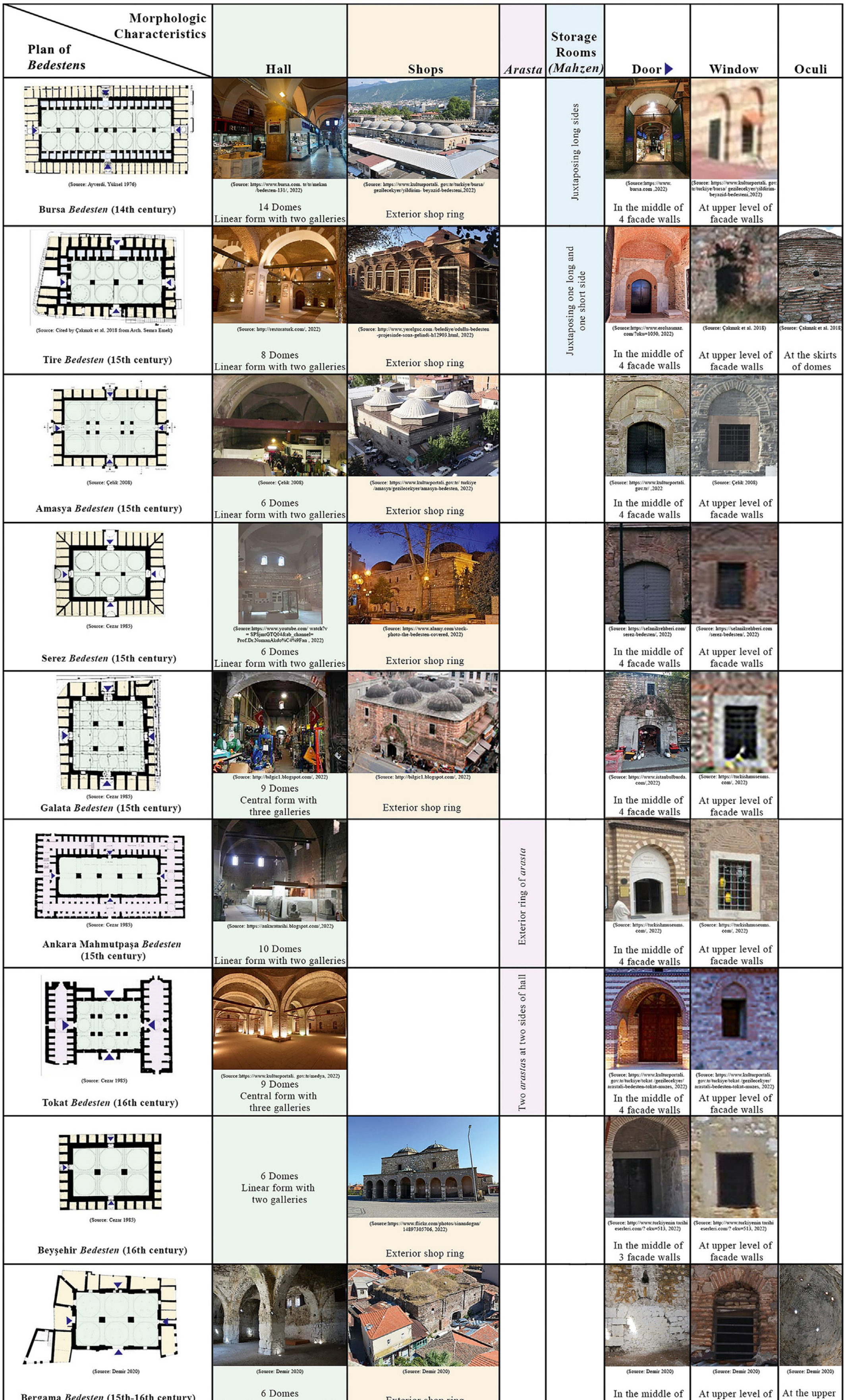


Fig. 14 Comparative study for spatial qualities. Source: The Authors.

thickness varies between 2 cm and 3 cm at the wall part. The span of the arch is 1.3 m and arch rise is 21 cm. Its voussoir thickness is 20 cm. Crown thickness of arch part is 74 cm and gained by the lay of brick rows side by side through the profile. Mortar thickness is 5 cm in the arch part (Fig. 12).

There are ten top windows in Bergama *Bedesten*. They are spanned with semicircular arches. Five of them have their own spanning element as a separate arch. The other five are directly placed under the type 1 arches that are integral parts of the walls. So, the type 1 arches constitute the upper part of top windows as well. The arch part was built with brick. The voussoir thickness is 25 cm for the first group, while the others have 27 cm. voussoir thickness. Wall parts were constructed with rough cut stone and brick in alternating order. The mortar thickness varies between 2 cm and 3 cm at wall part. The arch span varies between 0.75 m and 1 m. The arch rise varies between 25 cm and 35 cm. Crown thickness of arch part varies between 70 cm and 78 cm at different windows. This thickness is gained by the lay of brick rows side by side through the profile. Mortar thickness is 5 cm in arch part.

Their numbers within a dome vary between four and six. Their diameter is 22 cm and thickness is around 35 cm. These circular holes were created by the placement of cylindrical ceramic components within the brick lay of domes (Fig. 13).

4.3. Comparative study

Spatial and structural qualities of the case study are compared with similar examples, respectively.

4.3.1. Spatial qualities

Bergama *Bedesten* is compared with eight *bedesten*s: Bursa *Bedesten* (14th century), Tire *Bedesten* (15th century), Amasya *Bedesten* (15th century), Serez *Bedesten* (15th century), Galata *Bedesten* (15th century), Ankara Mahmutpaşa *Bedesten* (15th century), Tokat *Bedesten* (16th century), Beyşehir *Bedesten* (16th century). Excluding Galata, all were restored in compared examples (Fig. 14).

Spaces of a *bedesten* can be hall, shops, *arasta* and storage rooms (*mahzen)*. The major space is the hall. The hall space has a monumental height. It is dim; only top windows are present and some examples have small oculi on their domes. The hall design can be in linear or central form. Seven of nine examples excluding Galata and Tokat *Bedesten*s have linear halls with two galleries defined by pillars in the middle axis carrying the superstructure and allowing flow between gallery spaces. In Amasya *Bedesten,* two groups of four small pillars support the six domes. So, a sub-space was created within each pillar group. However, in the current state, it has four domes since the two out of the six domes were demolished. Tokat *Bedesten* has double pillars supporting its nine domes. The biggest one among them is Bursa *Bedesten* with fourteen domes. Ankara Mahmutpaşa *Bedesten* has ten domes and Tire *Bedesten* has eight domes, while remaining ones including Bergama *Bedesten* have 6 domes. Galata and Tokat *Bedesten*s have three galleries and nine domes. They have central form.

*Bedesten*s may have shops surrounding their exterior facades. Seven of nine examples excluding Ankara Mahmutpaşa and Tokat *Bedesten*s have an exterior shop ring composed of a single row of commercial units. They are entered from the street and not connected to the inner hall space. In Ankara Mahmutpaşa and Tokat examples, however, there is an *arasta* composed of two rows of shops with a linear circulation space in between. In Mahmutpaşa *Bedesten,* the *arasta* design is also like a ring encircling the facades of the *bedesten* hall walls. In Tokat *Bedesten,* two *arasta*s at two opposing sides of *bedesten* hall are present. There are entrance doors of hall which open to the *arasta*. The height of shop or *arasta* walls reaches nearly the half-height of the hall space facade walls.

Fig. 15 Lonca Masjid (a), Parmaklı Masjid (b), Bergama *Bedesten* (c), Tire *Bedesten* (d), Amasya *Bedesten* (e), and Serez Bedesten (f). Source: (a)–(c), The Authors; (d), Çakmak et al., 2018; (e), Çelik, 2008; (f), Stringfixer, 2021.

Plans of Buildings / Structural Elements	Roof	Dome and Transition Elements	Arch	Pillar	Wall
(Source: Ersoy 1989) **Lonca Masjid (15th–16th century)**	(Photo: Demir 2021) Two rows of brick sawtooth eave between over and under tile roof covering and walls Three rows of brick sawtooth eave between drum and over and under tile roof covering	(Photo: Demir 2021) Dome Span: 3.5 m and 5 m Type: One-Centered Depressed Dome Plastered at the interior Belt of Turkish Triangle providing transition from walls to domes Drum Form: Octagonal Material: Rough cut stones framed with bricks in an alternating order	(Photo: Demir 2021) Type: Bursa Arch Plastered at the interior Material: Brick and mortar (Photo: Demir 2021) Type: Two-Centered Tangent Relieving Arch- Plastered at the interior Material: Brick and mortar	–	(Photo: Demir 2021) Thickness: 1 m Material and technique: Rough cut stones framed with bricks in an alternating order exposed without plastering at the exterior, plastered and white-washed at the interior
(Source: Ersoy 1989) **Parmaklı Masjid (15th–16th century)**	(Photo: Demir 2021) One row of brick sawtooth eave between over and under tile roof covering and walls One row of brick sawtooth eave between drum and over and under tile roof covering	(Source: Cited by Ersoy,1989 from VGM Archive) Dome Thickness: 30 cm Rise: 2.70 m Span: 6.25 m Type: One-Centered Depressed Dome Plastered at the interior Belt of Turkish triangle providing transition from walls to domes Drum Form: Octagonal Drum Height: 0.75 m Material: Rough cut stones framed with bricks in an alternating order	–	–	Thickness: 1 m. Material and technique: Lower level-Rough cut stone masonry Upper level- Rough cut stones framed with bricks in an alternating order exposed without plastering at the exterior, plastered and white-washed at the interior
(Source: Demir 2020) **Bergama *Bedesten* (15th–16th century)**	(Photo: Demir 2020) One row of brick sawtooth eave between over and under tile roof covering and walls Two rows of brick sawtooth eave between drum and over and under tile roof covering	(Photo: Demir 2020) Dome Thickness: 35 cm Rise: 2.35–2.85 m Span: 6–6.30 m Type: Two-Centered Depressed Dome Material: Brick and mortar Plane triangles providing transition from walls to domes Drum Form: Octagonal Drum Height: 1 m Material: Rough cut stones framed with bricks in an alternating order	(Photo: Demir 2020) - Pointed relieving arches sunken within walls: Voussoir Thickness: 27 cm Crown Thickness: 35 cm Rise: 2–2.70 m Span: 4.20–6.15 m Material: Brick and mortar,white washed - Pointed arches spanning between walls and pillars: Voussoir Thickness: 27 cm Crown Thickness: 1.12 m Rise: 2.50–2.75 m Span: 5.95–6.05 m Material: Brick and mortar, white washed some plastered	(Photo: Demir 2020) Dimensions:156×147 cm² Material: Rough cut stone	(Photo: Demir 2020) Thickness: 0.72–1 m Material and technique: Lower level-Rough cut stone masonry Upper level-Rough cut stones framed with bricks in an alternating order exposed without plastering at the exterior, white-washed at the interior
(Source: Cited by Çakmak et al.2018 from Arch. Semra Emek) **Tire *Bedesten* (15th century)**	(Source: Çakmak et al. 2018) One row of brick sawtooth eave between over and under tile roof covering and walls One row of brick sawtooth eave between drum and over and under tile roof covering	(Source: Çakmak et al. 2018) Dome Thickness: 40 cm Span: 6.5 m Rise: 3 m Type: Two-Centered Depressed Dome Material: Brick and mortar Plastered and white washed at the interior before restoration Pendentives providing transition from walls to domes Drum Form: Dodecagon Drum Height: 1–1.20 m Material: Brick and mortar	(Source:restoraturk.com, 2021) Pointed relieving arches sunken within walls: Voussoir Thickness: 80 cm Rise: 2.2 m Span: 6.5 m Material: Brick and mortar - Pointed arches spanning between walls and pillars: Voussoir Thickness: 80 cm Crown Thickness: 1.5 m Rise: 2.2 m Span: 6.5 m Material: Brick and mortar, plastered and white washed before restoration	(Source:restoraturk.com, 2021) Dimensions:160×160 cm² Material: Rubble stone	(Source: Çakmak et al. 2018) Thickness: 1–1.30 m Material and technique: Rubble stone masonry exposed without plastering at the exterior, plastered and white-washed at the interior before restoration
(Source: Çelik 2008) **Amasya *Bedesten* (15th century)**	(Source: Çelik 2008) Two rows of brick sawtooth eave between lead roof covering and walls Two rows of brick sawtooth eave between drum and lead roof covering	(Source: Çelik 2008) Dome Thickness: 40 cm Span: 6.5 m Rise: 3 m Type: Two-Centered Depressed Dome Material: Brick and mortar Plastered and white washed at the interior before restoration Pendentives providing transition from walls to domes Drum Form: Dodecagon Drum Height: 1–1.20 m Material: Brick and mortar	(Source: Çelik 2008) -Pointed arches sunken within walls: Voussoir Thickness: 60 cm Rise: 4 m Span: 8.50 m Material: Brick and mortar, plastered and white washed -Pointed arches spanning between walls and pillars: Voussoir Thickness: 60 cm Crown Thickness: 1.5 m Rise: 4 m Span: 8.50 m Material: Brick and mortar, plastered and white washed	(Source: Çelik 2008) Dimensions:140×140 cm² Composed of four minor pillars each 5×5 m² Material: Cut stone	(Source: Çelik 2008) Thickness: 1.20–1.50 m Material and technique: Lower level-Rough cut stone masonry Upper level-Two rows of bricks and two rows of rough cut stone laid in an alternating order exposed without plastering at the exterior and interior
(Source: Cezar 1985) **Serez *Bedesten* (15th century)**	(Source:https://www.turkcebilgi.com/serez,2022) Two rows of brick sawtooth eave between over and under tile roof covering and walls One row of brick sawtooth eave between drum and over and under tile roof covering	(Source:https://www.youtube.com/ watch?v= SPSjmtGTQ04&ab_channel=Prof.Dr.NumanAkdo%C4%9Fan,2022) Material: Brick and mortar Pendentives providing transition from walls to domes Drum Form: Octagonal Material: Rough cut stones framed with bricks in an alternating order	(Source:https://www.youtube.com/ watch?v= SPSjmtGTQ04&ab_channel=Prof.Dr.NumanAkdo%C4%9Fan,2022) -Pointed relieving arches sunken within walls: Material: Brick and mortar - Pointed arches spanning between walls and pillars: Material: Brick and mortar	No data	(Source:https://www.turkcebilgi.com/serez,2022) Material and technique: Rough cut stones framed with bricks in an alternating order-Two rows of brick laid, one row of rough cut stone laid with two vertical bricks between stones, exposed without plastering at the exterior and interior

Fig. 16 Comparison of construction techniques and materials of Bergama *Bedesten* with monumental buildings in close-by environment and similar type *bedesten*s. Source: The Authors.

The last space type that may exist in *bedesten*s is storage room (*mahzen*) which can be entered only from the hall. Two of nine *bedesten*s have this space type: Bursa *Bedesten* and Tire *Bedesten*. In Bursa *Bedesten*, these storage rooms juxtaposed long sides of the hall. In Tire *Bedesten*, they juxtaposed one long and one short side as a partial ring. They are positioned between exterior shop row and hall space, so they are dark spaces without any window. From the outside, they are perceived as masses rising to half height of *bedesten* walls behind the exterior shop ring.

As architectural elements, they have entrance doors, windows and oculi. Eight of nine examples excluding Beyşehir *Bedesten* have four entrance doors which are placed in the middle of each facade wall. They are all arched excluding Beyşehir *Bedesten*. Seven of nine examples excluding Tokat and Beyşehir *Bedesten*s have doors with segmental arch which accomodates pointed or semicircular relieving arches. Tokat *Bedesten* has semicircular arched doors. Bergama *Bedesten* exemplifies the use of differently arched doors as two with semicircular arch and one with pointed arch in addition to the one with segmental arch. Beyşehir *Bedesten* has three entrance doors and they are in rectangular form by the use of a lintel cut stone. All of the *bedesten*s have top windows. Seven of nine excluding Tire and Bergama *Bedesten*s have rectangular top windows. Six of these seven examples excluding Beyşehir *Bedesten* have relieving arch designs above the windows. In four of six examples excluding Bursa and Tokat *Bedesten*s, the arches have relieving arches with pointed profile. In Bursa and Tokat *Bedestens*, semicircular profile is seen. Top windows of Tire and Bergama *Bedesten*s are with semicircular arches. In Tire *Bedesten* all of the window openings are directly placed under the relieving arches which are parts of the facade masonry walls. In Bergama *Bedesten*, the arch of window is either created by the relieving arch of facade masonry walls or has its separate arch.

Seven of nine excluding Tire and Bergama *Bedesten*s do not have any oculus in their domes. In Tire *Bedesten*, there are oculi ranging in numbers from 5 to 12 per dome. They are positioned close to the skirts of domes. In Bergama *Bedesten*, the oculi number ranges from 4 to 8 per dome. They are placed at the upper parts of domes.

In conclusion, in terms of hall design, mostly linear form with two galleries exists in examples. Their dimensions vary according to dome numbers. While Bursa, Ankara Mahmutpaşa, Galata, Tokat and Tire *Bedesten*s with dome numbers varying between eight to fourteen are bigger in hall size, Amasya, Serez, Beyşehir and Bergama *Bedesten*s are smaller with six domes. The dominance of exterior shop ring existence can be seen compared to *arasta* design. *Mahzen* space is also not so common among the examples. For architectural elements, entrance doors have generally segmental arch. Bergama *Bedesten* differs by the use of different arch types in doors. The use of rectangular top windows with relieving arches above them is mostly seen. Pointed profile is more common to semicircular profile for them. In Tire and Bergama *Bedesten*s, the placement of top windows directly under the relieving arch of masonry wall is preferred. Bergama *Bedesten* also exemplifies the design of top windows with separate semicircular arches. Tire and Bergama *Bedesten*s present the design of oculi in their domes.

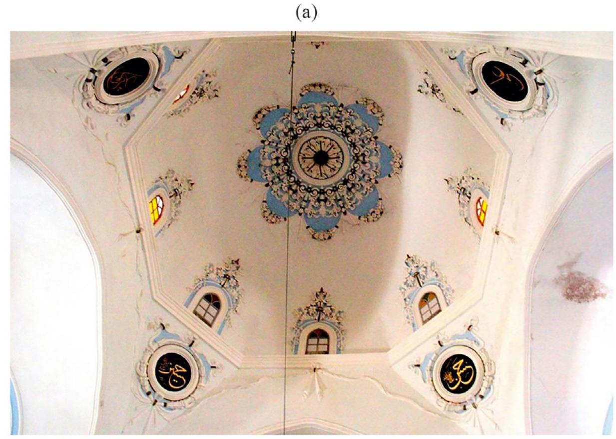
4.3.2. Structural qualities

Roofs, domes and transition elements, arches, pillars and walls of Bergama *Bedesten* are compared with those of Parmaklı Masjid and Lonca Masjid (15th−16th centuries) in Bergama and Tire *Bedesten* (15th century) in Tire, İzmir, Amasya *Bedesten* (15th century) and Serez *Bedesten* (15th century) (Fig. 15).

The majority of the similar cases and Bergama *Bedesten* are covered with over and under tiles. Only Amasya *Bedesten* has a lead roof covering in current situation. In general, one row or two rows of brick sawtooth eaves are seen between over and under tile roof covering and walls or drums. Bergama *Bedesten* exemplifies the use of both type as one row of brick sawtooth eave between over and under tile roof covering and walls, and two rows of brick sawtooth eave between over and under tile roof covering and drums. Only Lonca Masjid exemplifies the use of three rows of brick sawtooth eave. Till to the midth of the 15th century, brick sawtooth eave was used with the walls displaying alternating use of brick and stone (Ersoy, 1989).

The dome thickness of Bergama *Bedesten* is in an average value of other examples as 35 cm. The most similar span and height values to Bergama *Bedesten* (6—6.30 m and 2.35—2.85 m) are seen in Tire *Bedesten* (6.50 m and 3 m). As the dome material, the use of brick and mortar is observed for the unplastered ones. Bergama, Amasya (15th

(a)



(b)

Fig. 17 Plane triangles of Bergama *Bedesten* (a) and Bergama Ulu Mosque (b). Source: (a), The Authors; (b), Erolsasmaz, 2022.

century) and Tire (15th century) *Bedesten*s have two-centered depressed domes. The use of oculi in *bedesten*s is only seen in Bergama and Tire *Bedesten*s.

Majority of the examples including Bergama *Bedesten* have octagonal drums with an alternating order of brick and stone materials. Only Tire *Bedesten* has dodecagon drums built with brick. The drum height of Parmaklı Masjid (0.75 m), Bergama *Bedesten* (1 m) and Tire *Bedesten* (1—1.20 m) show similar values. Amasya *Bedesten* differs with 2 m drum height (Fig. 16).

Bergama *Bedesten* differs from all of the compared examples by the use of plane triangles in transition to the dome. In historical research, the use of pendentives was seen for the *bedesten*s, too. However, in Bergama Ulu Mosque (14th century) which is one of the last representatives of the multiple unit basilical planned mosques in Anatolia, the use of plane triangles is seen at the transition to its middle dome (Ersoy, 1988). This creates a similarity to Bergama *Bedesten*, although it was built in an earlier period (Fig. 17).

*Bedesten*s have two basic types of arches as relieving arches sunken within walls and load-bearing arches spanning between pillars and walls. The majority of the structures including Bergama *Bedesten* have pointed arch profiles. Lonca Masjid has one relieving arch with two-centered tangent profile and another relieving arch in Bursa arch form. Bergama *Bedesten* differs from the other structures with the minimum value of the voussoir thickness for the arches as 27 cm. For the crown thickness of load-bearing spanning arches between pillars and walls, Bergama *Bedesten* arches (1.12 m) have similar values to the

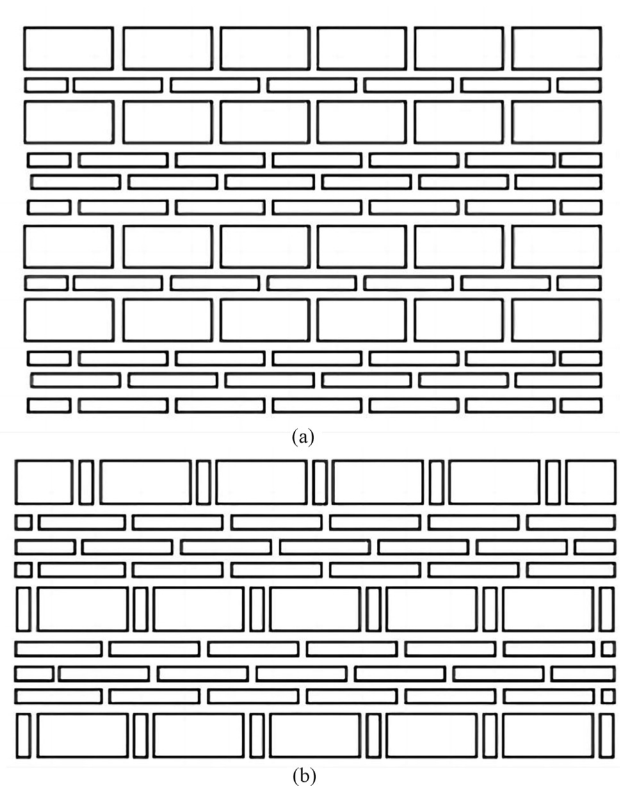


Fig. 18 Walls with vertical (a), and composite alternating order (b). Source: Kutlu (2017).

arches of Tire and Amasya *Bedesten*s (1.5 m). For the span and height, Bergama *Bedesten* (5.95—6.05 m span, 2.5—2.75 m rise) and Tire *Bedesten* (6.5 m span, 2.2 m rise) display similarity. All of the arches seen in the compared structures are out of brick and mortar.

As the pillar design, Bergama, Amasya and Serez *Bedesten*s show similarity with the number of them as two while for the dimensions, Bergama and Tire *Bedesten*s are similar by the values as 156 cm × 143 cm. and 160 cm × 160 cm, respectively. Amasya *Bedesten* has a unique design by the composition of four minor pillars creating the two main pillars. For the material usage, Bergama, Tire and Amasya *Bedesten*s display different choices as rough cut stone, rubble stone and cut-stone.

All of the examples excluding Tire *Bedesten* show the alternating use of brick and stone materials in their walls. This quality in wall construction is classified under two basic methods as horizontal alternating order and vertical alternating order. In horizontal alternating order, brick and stone materials are placed on the same row, while in vertical alternating order, they are placed on separate rows. When these two techniques are used together, it is called as composite alternating order (Kutlu, 2017) (Fig. 18).

In the 14th century, the use of rough-cut stone and rubble stone with brick was common while in the 16th century the choice of cut stone-brick usage was increased. In the 15th century, the balance for the preference between these two methods was seen (Kutlu, 2017). In Bergama *Bedesten*, Serez *Bedesten*, Parmaklı Masjid and Lonca Masjid, the composite alternating order can be seen. While Bergama *Bedesten*, Parmaklı Masjid and Lonca Masjid display one by one use of brick and stone rows in vertical and horizontal orders, Serez *Bedesten* differs among them by the use of two rows of brick in horizontal and vertical orders creating the composite order. Amasya *Bedesten* has vertical order. Bergama *Bedesten*, Parmaklı Masjid (Fig. 19) and Amasya *Bedesten* also display rough-cut stone masonry order till to the half height of them in their walls.

There is a unique design in the walls of Bergama *Bedesten* as the thickening of them at the parts where the arches integrate to the walls both towards inside and outside and at the corner connections of perpendicular walls. This quality was not seen in any other *bedesten* design during historical research and comparative study. In Bergama Ulu Mosque (14th century), the thickening of walls towards inside is seen and the quality observed in the Bergama *Bedesten* can be the continuation and development of this design (Fig. 20).

As a result, Bergama *Bedesten* displays similarities to the structures belonging to different centuries in terms of its construction technique. However, some of them can be evaluated as a continuation of earlier designs within the close-by environment, while some of the overlapping qualities can be beneficial for the dating of the building. Since the plane triangle usage is common in Principilaties Period, the similarity between Bergama *Bedesten* and Bergama Ulu Mosque (14th century) can be assessed as the continuation of an earlier construction technique. The wall thickening can be classified within the same category. However, the wall construction technique similarity with Parmaklı Masjid (15th–16th century), Lonca Masjid (15th–16th century), Amasya *Bedesten* (15th century), and Serez

Bedesten (15th century), increases the possibility for Bergama *Bedesten* to be built in 15th–16th centuries.

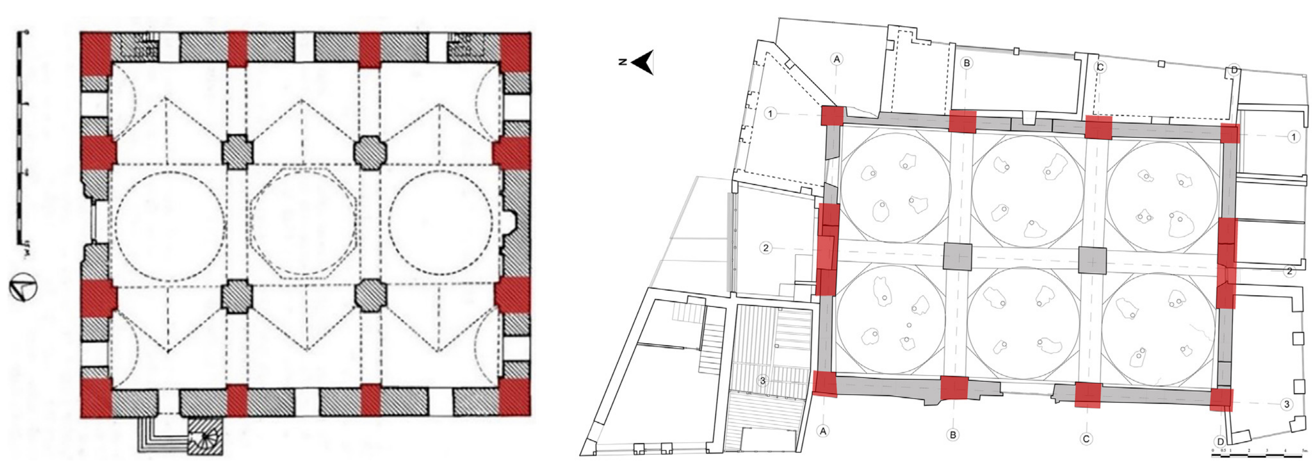
5. Discussion

In this part, the derived construction technique and material usage study results about Bergama *Bedesten* are discussed with the structural theory of masonry by Heyman and the numerical self-weight analysis results of the structure.

Structural theory of masonry defines this system as the composition of stones, bricks, etc., sometimes laid by the use of mortar filling the gaps between them. Due to compressive stress, stability of the structure is provided. The basic three assumptions for masonry are no tensile strength, unlimited compressive strength and no sliding failure. In this theory, some limiting states are defined for structural element types as arches, domes, vaults, etc. The geometrical factor of safety theorem for arches suggests that the minimum thickness of an arch to accommodate thrust line should be at least 10% of its radius (Heyman, 1995). In Bergama *Bedesten*, diameter interval for arches varies between 4.15 m and 6.15 m. According to the equation, the arches that have up to 5.4 m span, validate the geometrical factor of safety by having the vouissoir thickness of 27 cm. However, the arches spanning between pillars and masonry facade walls with a higher distance (5.95–6.05 m) than 5.4 m, have also 27 cm voussoir thickness. The thin section by 27 cm is a rare quality for

(a) (b)

Fig. 19 Wall technique of Bergama *Bedesten* (a), and Parmaklı Masjid (b). Source: The Authors.



(a) **(b)**

Fig. 20 Thickened walls of Bergama Ulu Mosque (a), and Bergama *Bedesten* (b). Source: (a), Revised from Ersoy (1988); (b), The Authors.

Bergama *Bedesten* in comparison with similar cases, as well.

$$r \times 0.1 = 2.075 \text{ m} \times 0.1 = 0.2075 \text{ m}, \quad (1)$$

$$r \times 0.1 = 3.075 \text{ m} \times 0.1 = 0.3075 \text{ m}. \quad (2)$$

In static structural analysis including dead load and standard earth gravity, the maximum principal stress values exceed the limit parameters for brick masonry in these load-bearing arches (Appendix A). Because the arches keep their structural integrity in current condition and only some displacements were observed for all of them, it can be deciphered that this up to 3 cm missing thickness increases vulnerability risk but does not cause a major danger for the structural system.

When domes are considered, they are shell elements that behave as a membrane. A shell is a curved surface and the resistance in this element type is provided by the forces acting in the surface. Because of membrane force distribution along the surface, it is enough for a shell element to have a small minimum thickness compared to arches against local compressive buckling. The minimum required thickness (t) of a dome to accommodate thrust line within the geometry is calculated by the following equation by considering the Radius (R) (Heyman, 1995).

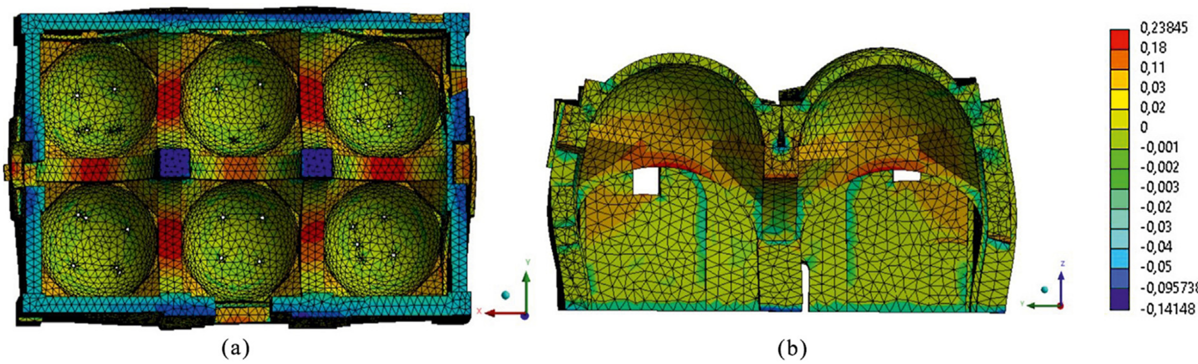


Fig. 21 Maximum principal stress values exceeding limit tensile strength of brick masonry in load-bearing arches and under limit in domes shown in ceiling plan view (a) and transversal section view (b). Source: The Authors.

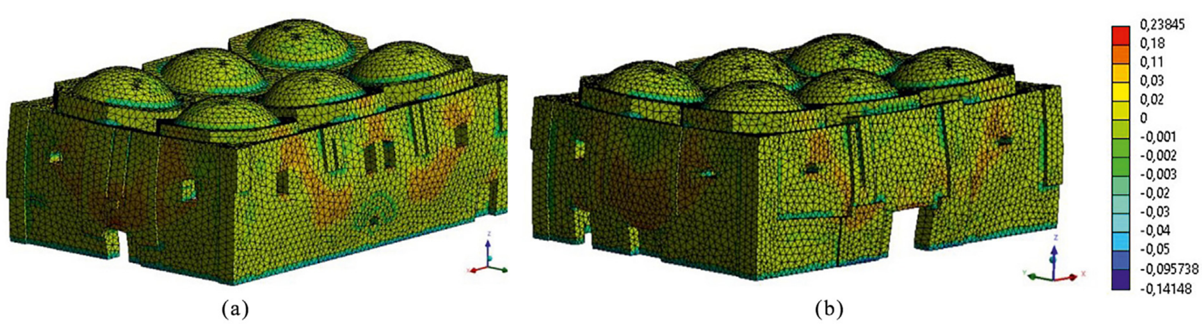


Fig. 22 Maximum principal stress densified areas at arch-wall integration levels in east, south (a) and north, west (b) walls. Source: The Authors.

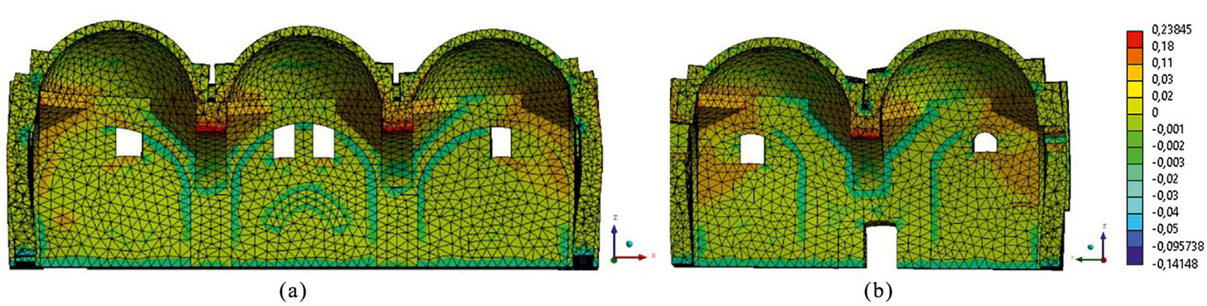


Fig. 23 Plane triangles with maximum principal stress values exceeding limit tensile strength of brick masonry in longitudinal (a) and transversal (b) section views. Source: The Authors.

$$t/R = 0.042. \tag{3}$$

For Bergama *Bedesten*, the dome spans vary between 6 m and 6.30 m. The required minimum thickness interval can be found by the use of related formulas (4), (5).

$$t/3 = 0.042, \quad t = 0.126 \text{ m}; \tag{4}$$

$$t/3{,}15 = 0.042, \; t = 0.132 \text{ m}. \tag{5}$$

According to the results, the minimum required thickness is nearly 13 cm for domes. In Bergama *Bedesten* the thickness of domes is 35 cm, which is higher than the minimum required value. In other comparative study examples, the dome thicknesses vary between 30 cm and 40 cm.

In the self-weight analysis results, domes of the *bedesten* display safe condition. The maximum principal stress values are under the limit tensile strength values of the brick masonry. The rare quality as the oculi placement in domes also does not create any risky state by maximum principal stress (Fig. 21). Although the use of oculi is a rare characteristic for *bedesten* building type, the use of this quality is seen in Ottoman period baths (14th–16th centuries), e.g., Hacı Hekim Bath, Küplü Bath in Bergama showing that it is the construction technique of experienced knowledge.

The thickening of the walls at the arch-wall integration zones of Bergama *Bedesten* is a rare quality among other local masonry monuments (2 out of 7: Ulu Mosque and Bergama *Bedesten*). It is an appropriate application since the stress-densified areas emerged after the self-weight analysis in the structure at these locations (Appendix A), but they are under the limit by principal stress values not threatening safety under dead load thanks to this sectional thickness quality (Fig. 22).

The plane triangle is another rare quality that was preferred in two monuments of Bergama: the *Bedesten* and Ulu Mosque. There are areas exceeding the limit tensile strength value of brick masonry at the corners (Appendix A). Thus, plane triangles create vulnerable areas in the structure (Fig. 23).

6. Conclusions

This study detects the consciousness level in authentic architectural heritage designs through the documentation of construction techniques of a historic masonry building, comparative study, and assessment of the structural designs by the structural theory of masonry and self-weight analysis. The examined case study is Bergama *Bedesten* (15th–16th century). Some construction techniques used in the *bedesten* add rare value to the structure: the thin section as 27 cm in load-bearing arches, the use of oculi in domes, plane triangle usage as transition elements, the thickening application at the parts where arches integrate to the walls and at the corners where orthogonal walls intersect. Some of these characteristics increase the structural resistance while some cause vulnerability. The load-bearing arches with the thinnest section in compared examples lead to the vulnerable areas around keystone levels. Since this quality is not seen in any of the other examples, the completely new trial of a construction technique causes vulnerability in this state. The rare quality as the oculi in the domes does not lead to a risky state. Because it is a common quality for bath structures of the Ottoman Period, it can be evaluated as the adaptation of a construction tradition experienced as sound in a different building type of the period not causing any weakness. The plane triangles as a rare quality for the period of Bergama *Bedesten* create risky zones at the structure as revealed in the self-weight analysis results exceeding limit values. It can be evaluated as the sustaining of the local construction tradition of the studied settlement, which was no more preferred in the same period monuments within the studied region causes vulnerability. Another rare quality for the periodic qualities and similar type buildings is the pillar-like thickened portions at the walls corresponding to load-bearing arch integration levels to walls. It displays a successful result under self-weight analysis both showing the stress-densified areas at that locations proving the risk and the elimination of risky situations by the lower values than the limit. This application can be also explained by sustaining of local construction tradition of the previous centuries, which was abandoned in the same period monuments, however, this time contributing to structural safety. In conclusion, the proposed methodology allowed the determination of the frequency of preference of specific construction techniques for a historic monumental masonry building and identify the safety state for the related designs. According to the derived results, the rare qualities in the construction technique of Bergama *Bedesten* either have the potential to create risky situations or contribute to structural safety. Therefore, there is no total consciousness in structural design preference for the studied *Bedesten*, but the structural designs that are often preferred in the monuments built at the same period have low vulnerability, exemplifying conscious preferences. The vulnerability level of the alternatively developed structural elements, which were preferred in the period monuments in place of the rare elements of Bergama *Bedesten*, e.g., pendentives instead of plane triangles, should be assessed with future work in order to clarify the consciousness in the change of construction traditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.foar.2023.08.002.

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