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Article

Simplified structural analysis method for traditional timber buildings with cross frame

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ABSTRACT

The purpose of this article is to develop a simplified structural analysis method for determining the load-bearing capacity of traditional buildings with timber frames and infill adobe walls, which have a very important architectural value in our cultural heritage, against various loads and environmental effects. Numerical models of the existing building are prepared and structural analyzes are performed before the repair and strengthening works of historical buildings. The structural analysis of traditional timber buildings differs from the analysis approaches of today's modern structures. In the structural analysis of such a building, criteria such as member sizes of structural frames, connection details, and material properties of unit elements may not be analyzed with a simple approach as the methods used in modern structures. For that reason, it is necessary to develop a simplified structural analysis method to reach the closest results in the conservation and strengthening studies of traditional timber buildings. The simplified structural analysis method developed in this article is applied in Boyabat Mehmet Kaya's House. The building is analyzed in three different scenarios with the proposed structural analysis method. The compression stiffness of the T/C (Tension/Compression) friction isolator element is estimated in a different way, in the first scenario, there are no windows and door openings or deterioration in the adobe walls of the building. In the second scenario, there are door and window openings in the infill adobe walls. In the third analysis case, there are infill adobe walls where material deterioration is effective and damage is observed in certain parts of the building. In the calculations attained, the displacements at the specified points of the building indicate significant findings about the structural behavior of the building according to the compressive stiffness.

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INTRODUCTION

All the necessary actions for the conservation of historical buildings bring together many interdisciplinary sciences such as architecture, engineering, archeology, art, and history. The engineering calculations of a historical building that requires repair and strengthening are quite complex. Due to its uncommon material characteristics and geometry, it is difficult to comment on its structural behavior without performing certain structural analyses.

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For this reason, structural analyses should be carried out by considering the specific material properties and geometry. However, deformations and displacements that may occur in the structure can be estimated within the framework of the basic principles of engineering and general physics rules by simplifying the load-bearing structure during the planning phase. Today, many engineering software have been developed that can perform these analyzes in line with the needs. Modeling and structural analysis have been developed and accelerated. It is of great importance to interpret these results of analysis of software packages, which provide a great convenience for the user. In this study, it is aimed that the analytical evaluation of a historical structure with a timber frame through a simplified model that can be easily evaluated by all related disciplines.

The increasing level of income and welfare in societies increases the awareness of the importance of preserving structures with historical and cultural value and passing them to future generations. The conservation of buildings with historical and cultural value is a process that requires the cooperation of different disciplines and requires a comprehensive evaluation of many parameters. However, the general condition of the structural system is slightly more prominent among these parameters for the structure to survive robustly. While the conservation of monumental structures representing the history and culture of countries requires institutional interventions, there are individual interventions for traditional buildings (Dutu et al., 2018; Li, 2022). It is almost impossible to implement a common structural analysis method for traditional timber buildings, each with different materials and structural members. In the planning phase of the strengthening and conservation process, the current structural performance of the building must first be determined. A simplified calculation method that accurately reflects the structural condition of the building facilitates an orderly start to conservation planning.

Timber-framed and adobe-filled traditional buildings are found in many parts of the world, many of which were built in earthquake-prone areas. They are widely preferred according to geographical location and flora since they can be built at low costs thanks to the use of easily available materials such as wood, stone, and soil. Most of the masonry and timber buildings made using these materials have survived to the present day and continue to be used. It is known that traditional timber-framed buildings are earthquake-resistant structures and suffer very little damage during seismic movements. For this reason, their survival has increased the reliability of the building system (Güçhan, 2018; Kalkan Okur et al., 2021).

In recent years, there has been an increasing momentum in scientific research on structural analysis and numerical modeling of traditional timber buildings. Experimental and analytical calculations have gained importance by supporting timber frame systems with intermediate elements such as natural masonry stone, brick, and adobe. Frame wall units formed in different materials, frame systems, and binding types were manufactured and subjected to structural analysis under various loadings. Analysis results such as displacements, forces, and failure mechanisms of the system shed light on how the structure will behave (Aktaş, 2017; Vieux-Champagne et al., 2014; Sandak et al., 2019; Chand et al., 2020; Yazgan and Unay, 2020; Lukic et al., 2018; Huang et al., 2018; Liang et al. 2022). However, the lack of experimental data on the structural systems and joint details of traditional buildings with timber frames and infill adobe walls makes it difficult to prepare and measure numerical models for structural analysis of existing buildings (Fritsch et al., 2019). Since each structure has its significant properties regarding materials, structural system, details, the laboratory experiments or the numerical modelling techniques do not provide a general structural analysis method. Although the assumptions made for the estimation of material properties and joint details of the adobe, which require a non-linear analysis method due to its characteristics, show mathematical results compatible with the experimental sets prepared for the selected unit elements. Many different results can be obtained from the numerical models to be prepared for the entire building. This increases the importance of a simplified numerical modeling and structural analysis method, especially during the protection and strengthening planning phase (Bağbancı, 2013; Günaydın et al., 2023).

With the diversification of numerical modeling methods, the analysis of masonry structures has become prominent. Aguilar et al. (2019) performed modal analysis, experimental modal analysis, seismic capacity assessment and pushover analysis, and limit analysis by applying accurate geometric modeling and simplified analytical methodology to a historic adobe structure using a laser scanner and photogrammetry. The application of this methodology allowed us to determine the performance levels of an adobe church against different seismic scenarios. The results showed that the church can remain intact until occasional earthquakes with a return period of 72 years. However, the results emphasized that rare earthquakes (return period of 475 years) can create an unsafe structural condition with partial collapse of structural elements. Sandak et al. (2019) used LVDTs to investigate a timber-framed stone infill wall structure within the ductile elastic limit and to determine its behavior under static-seismic loads. In his study, Dutu (2021) focused on timber framed infill walls in three different contries in detail. He emphasized the importance of this type of structure and conducted experimental studies to explain its structural behavior. As a result, he explained the resisting mechanisms of structures that have survived against seismic effects for many years. He experimentally demonstrated that timber frames with infill walls and diagonal members resist earthquake effects to a significant degree (REF Conclusion). Referring to Dutu's (2021) study, Gülkan and Langenbach (2021) emphasized the importance of hımış structures, which are frequently encountered in rural areas in Türkiye.

In Meybodian et al.'s (2020) study, various walls were designed and analyzed using adobe which is known as a sustainable material. Locally available, sustainable reinforcing materials such as palm fibers and reeds were preferred as natural reinforcing materials and one wall panel was reinforced with a special type of plastic mesh for comparison. The results are described in terms of lateral load displacement, ultimate strength, displacement capacity, ductility factor, energy dissipation, and equivalent viscous damping. The experimental findings revealed that the structural response of adobe walls can be significantly improved using natural reinforcing materials. Jiménez et al. (2021) classified the Damage Vulnerability Index Method for the seismic evaluation of hybrid timber-masonry buildings. Their method is based on the execution of a detailed numerical study of this specific structural typology to calibrate the scores assigned to the irregularities of the structural system, the type of storey, and the state of preservation of the building. A sensitivity analysis of the seismic capacity was developed by performing pushover analyses with several models corresponding to realistic variations of each structural or material parameter Jiménez et al. (2021) and Vieux-Champagne et al. (2014) analyzed the seismic performance of timber-framed structures filled with natural stone and earth mortar using three-scale experiments in which both cyclic and monotonic loading were considered. The first scale was to determine the local effect of the number of nails under two loading directions, the second scale was based on the foundation cell detail and the third scale was based on the shear wall size analysis. The specimens were analyzed as a whole wall without any openings (doors or windows). The effect of infill on stiffness, maximum load, or equivalent viscous damping was analyzed. This study was then compared with three other experimental studies on the same type of traditional structures to obtain answers regarding the seismic-resistance behavior of these structures.

Literature review shows that there are few studies in which timber-framed natural adobe walls are applied together as a hybrid system, the existing studies have contributions to primarily experimental approaches, while numerical studies require intensive engineering knowledge. For this reason, this study aims to simplify the prediction of the behavior of timber frame system filled with adobe walls numerically.

Especially in Türkiye, there is no structural studies on timber framed adobe infill walls. For this purpose, it is necessary to develop a structural calculation method that can be easily interpreted (displacements, internal forces, and stresses in the structural system elements) by all related professionals working in various stages of conservation and restoration field to protect the historical architectural heritage in earthquake prone zones. In this study, the displacements of timber framed adobe fill walls under structural loads are presented with different scenarios to be more easily understood. Timber-framed adobe fill walls, which are experimentally specified in the literature studies, are defined as T/C isolators (tensile/compression isolators) at the connection points in numerical modeling. The scenarios (TFwAF-01, TFwAF-02, TFwAF-03, and TFwAF-04) were explained, TFwAF-02 and TFwAF-03 were applied by modeling the structure selected as a case study with the finite element method. With the use of simplified calculation method, the analyses performed on the numerical model, which has been prepared with the information obtained from the building survey, give results that help to determine the behavior of the structure, especially in terms of displacements.

CHARACTERISTICS OF STRUCTURAL SYSTEMS OF CONVENTIONAL TIMBER BUILDINGS

Timber is one of the oldest building materials used in construction in many parts of the world. The construction of timber structures dates back to the 15th century and is known to have continued until the 1960s (Doğangün et al., 2006).

Although timber is widely used in the world, its use in Türkiye has remained at a very low level compared to other construction systems. The use of wood as the main structural frame of buildings in Türkiye has decreased significantly since the 1940s with the use of reinforced concrete, stone, and steel in the construction industry. Wood is used much more in buildings, especially in the northern countries of Sweden, Norway, Finland, Canada, and the USA, as well as in Japan, New Zealand, and Australia, than in Turkey (Özdemir et al., 2008).

It is known that, wooden structures have been replaced with other materials such as stone, brick and reinforced concrete due to the damages of various natural disasters. In recent years, timber materials have become prominent one more time with the popularized sustainability paradigm and this has led to a renewed focus on traditional timber construction systems. The use of new types of building materials as hybrids with timber building systems in contemporary construction is becoming more widespread.

As in many regions of the world, it is possible to encounter various timber construction systems in Türkiye which are used to be preffered extensively in the past. Due to the high seismic risk, the availability of materials, and the climatic conditions, traditional timber construction techniques have been applied, especially in Western Anatolia.

Timber Building Construction Systems Used in Türkiye

Timber structures can be considered among the cultural heritage of people living in this region. Traditional architecture in Turkey has many unique styles (Doğangün et al., 2006; Özdemir et al., 2008; Aras, 2013). Turkish-Ottoman Houses, which have been shaped by the cultural, social and climatic factors, are the most important examples of timber buildings recognized worldwide (Özdemir et al., 2008; Saatçi, 2020).

In timber buildings, the loads are encountered by posts, beams, purlins, bases, and diagonal elements and they transferred to the building foundation. In addition, in these structural systems, there are there can be other components which do not present any bearing properties such as flooring and cladding elements. Walls, made out of adobe or other infill materials and placed between timber members, are among the common examples (Saatçi, 2020).

Traditional timber buildings in Turkey can be classified as houses consisting of logs or planks, unfilled frame systems (bağdadi/wood veneer), and infilled frame systems (hımış/dizeme/muska dolma).

Log Houses

It is called "canti" (log house), where lightly processed logs or planks are superimposed and fixed in both ends. The walls, formed with logs or planks, function as both carriers and dividers (Figure 1a and b). In traditional Turkish log houses, members lying horizontally transfer vertical loads from top to bottom to the foundation. Even if such a structural system is sufficient for vertical loads, it may not be able to withstand the lateral loads due to loosened ends by the effects of shear forces during a destructive earthquakes (Doğangün et al., 2006; Yağcı Ergun et al., 2021).

Unfilled Frame Systems (Bağdadi/Wooden Coating)

Bağdadi is a type of plaster which is often applied with slats over the frame. When plastering the front and back parts of the walls, the spaces in between are ventilated with inlet-outlet holes. This provides insulation. Bağdadi is made with thick or thin slats. Wood coating, on the other hand, is a type of wall formed by hitting wooden coating boards on the structural system elements. These cladding boards can be overlapped or flat. (Yağcı Ergun et al., 2021; Aktaş Erdem et al, 2011; Silveira et al., 2012). In Turkey, timber houses are generally one, two, or three storey buildings. The ground floor of these buildings was usually built with stone or adobe walls. Hımış and bağdadi construction techniques can usually be used together for different levels. Figure 2a shows the plaster of bağdadi, while Figure 2b shows an example of the ground floor bağdadi, a construction using hımış.

Infilled Frame Systems (Hımış/Dizeme/Muska Dolma)

The walls formed by filling he gaps between the frame elements with masonry (brick, adobe, briquette etc.) materials are called Hımış, which is one of the most common systems used in Anatolia. The masonry infill materials differ according to the climate and characteristics of the region. The mortared or unmortared stone infill placed in the triangular gaps created with diagonal elements is called Muska Dolma. The meshing consists of timber elements placed horizontally or vertically between the roof systems. There are examples of applications between timber elements with or without mortar. In Figure 3a, adobe filled hımış structures, in Figure 3b, a 3 storey adobe filled structure with a stone foundation from the west part of the Black Sea Region are shown.

A SIMPLIFIED STRUCTURAL ANALYSIS METHOD FOR TRADITIONAL TIMBER BUILDINGS

Structural analysis of historical and traditional timber structures is different from the analysis of contemporary structures. Each of the elements that make up the structural system of a traditional timber building has unique details and material properties according to their sizes and connection

Figure 1. **(a, b)** Examples of timber structural systems created by sequential alignment of planks and logs Artvin/Türkiye.

Figure 2. **(a)** Bağdadi system technique (Sinop) **(b)** Bağdadi and half-timbered system technique (Sinop).

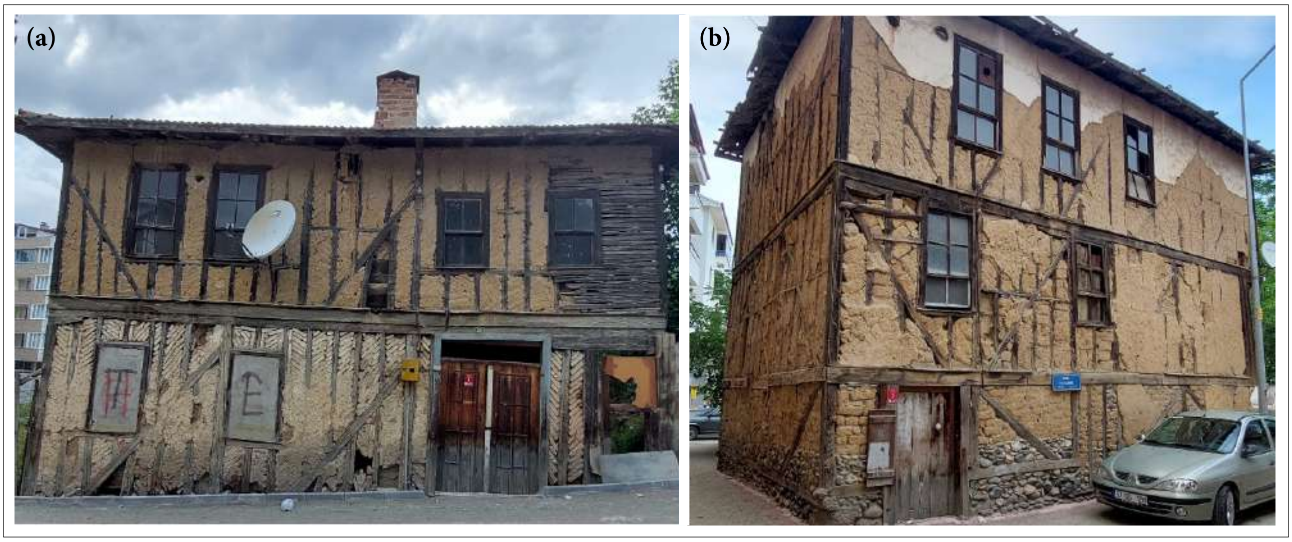

Figure 3. **(a)** Example of Hımış and partial bağdadi structure, **(b)** Basic stone filling hımış system structure.

types. Due to these features, it is not always possible to apply the general engineering analysis practice directly, as in the engineering calculations of reinforced concrete and steel structures. Defining the material properties of wood and adobe together, requires laboratory experiments and highly complex numerical modeling techniques (Aktaş Erdem et al., 2011).

It is necessary to develop a simplified analysis method to reach the most accurate results in the planning phase of the conservation and strengthening works of traditional timber buildings. First of all, a plane frame analysis model is prepared for this approach. As shown in Figure 4, to examine the structural interaction of timber frames with adobe blocks, a numerical model of a 3 m high plane frame with a 4 m span, including timber beams and posts as well as adobe blocks is prepared. The cross-sectional dimensions of the timber beams and posts are 200 mm × 200 mm and the thickness of the adobe wall is 200 mm. As summarized

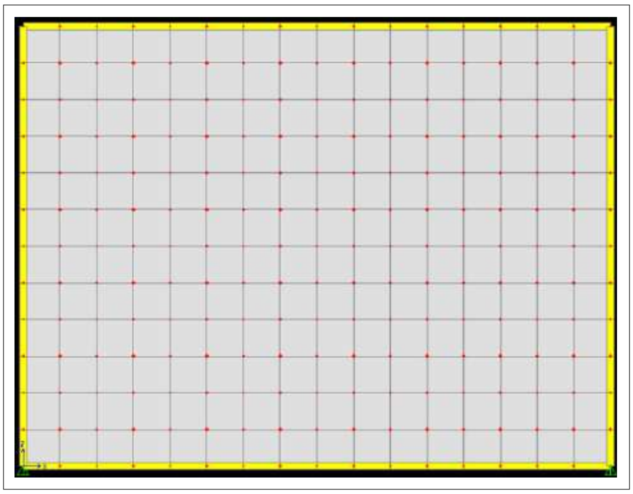

Figure 4. Numerical model for the first analysis (TF-wAF-01), Timber frame with infill adobe wall.

in Table 1, the modulus of elasticity for wood is assumed as E=10000 MPa and for adobe as E=225 MPa. These data were taken from the "Guide to Managing Earthquake Risks for Historical Buildings" prepared by the General Directorate of Foundations (Vakıflar Genel Müdürlüğü, 2017; Ahşap Yapıların Hesap ve Yapım Kuralları, 1979; Duman and Ökten, 1988). Since adobe is not produced according to a certain mixing procedure and specification, it can present varying material properties even within the same building. Because of experimental studies conducted to determine the mechanical properties of adobe material used in traditional buildings, approximate values based on observations for the modulus of elasticity of adobe have been adopted. Silveira et al. (2012) estimated the modulus of elasticity for adobe from the stress-unit deformation curve obtained by simple compression experiments. On the other hand, Vicente and Torrealva (2014) proposed the adobe's modulus of elasticity as 300 times the compressive strength in their experimental study of a typical infilled adobe timber building. In the current earthquake specification in Türkiye and some scientific publications about masonry structures for brick masonry walls, the modulus of elasticity is recommended as 300 times the compressive strength of masonry materials (Türkiye Bina Deprem Yönetmeliği, 2018; Bayülke, 2011; Bayülke, 2018). In this study, the modulus of elasticity of the adobe wall is accepted as E=225 MPa, assuming that the compressive strength of a typical adobe masonry wall is 0.75 MPa (Vakıflar Genel Müdürlüğü, 2017).

In the numerical models, four consecutive analyzes were carried out with the SAP2000 finite element analysis software. The most appropriate way to examine the behavior of the timber frame with infill adobe walls is to calculate the displacements in the frame. Therefore, in parametric analysis, the weight of the timber frame and infill adobe walls is not taken into account. To observe the change in the displacements, a point force of 500 kN is applied as a first loading case at the upper left corner of the frame along the positive x-axis (in the horizontal direction) and 500 kN in the negative x-axis direction at the same point as a second loading case. As shown in Figure 4, in the first analysis (TFwAF-01), the timber frame defined by FRAME elements and the infill adobe walls defined by SHELL elements are modeled as a whole. Although it is known that there can never be a perfect combination between the beams and posts forming the timber frame and the infill adobe walls as in the (TFwAF-01) numerical model. This numerical model has been prepared to observe the alteration in the next modeling options. It is fixed with a simple support from the point at the two corners of the base assuming that the examined frame is on any floor of the building, on any surface, or the partition wall.

In the second analysis model (TFwAF-02) as shown in Figure 5, in order to consider a more realistic behavior on the joint surface of the timber frame and the infill adobe, T/C friction isolator elements that do not transmit the tensile forces in a way that corresponds to each SHELL element, but only transmit the compressive forces are applied. There will be no physical bond between the infill adobe and the timber frame in the regions where tensile stresses are applied as a result of the forces in the positive x and positive y directions considering that the tensile strength of the adobe is very small and there is no bond based on tensile stress between the timber frame and the infill adobe wall, (Jiménez & Pelà, et al., 2022). In the numerical model of the analyzes performed with the non-linear static calculation method, the compressive rigidity of the T/C friction isolator element is approximately determined

Table 1. Timber and adobe material properties used in finite element analysis

Materials	Compressive strength MPa	Modulus of Elasticity MPa (kN/m^2)	Unit weight (kN(m^3)
Timber	*	10000 (10000000)	10
Adobe	0.75	225 (225000)	15

*The tensile and compressive strengths of timber in the direction of the fibers (parallel) and perpendicular to the fibers are different. The safety stresses are 10.5–11.0 MPa in tension parallel to the fibers, 11.0–12.0 MPa in compression parallel to the fibers and 2.0–3.0 MPa in compression perpendicular to the fibers for Class I pine-oak and beech, provided that they are reduced in case of oblique force. Timber is not to be worked perpendicular to the fibers, the safety stress is assumed to be zero.

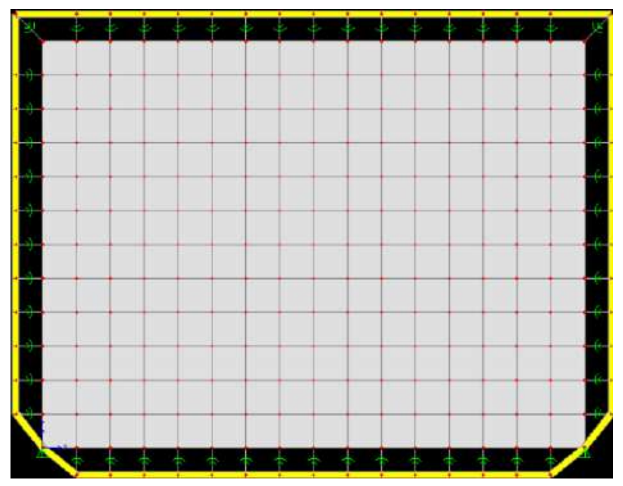

Figure 5. Numerical model for the second analysis (TFwAF-02).

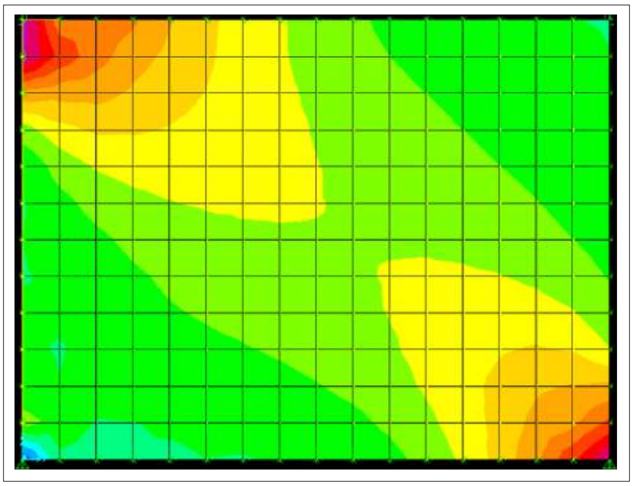

Figure 6. Distribution of compressive stress in adobe by (TFwAF-02) analysis.

due to the accepted compressive strength for the adobe. Although the software can be runned with a single point between the timber frame and the adobe, to better control the behavior of the structure during the structural analysis, T/C friction isolator elements are modeled with two-point LINK elements by leaving a 5 mm gap between the timber frame and the infill adobe wall.

The aim of these two analyzes is to monitor the interaction between the timber frame and the infill adobe wall with non-linear elastic static calculations more realistically with a numerical model using tension-compression controlled T/C friction isolator elements. In the first analysis performed with the (TFwAF-01) model, the largest displacement is calculated as Δx=22.15 mm, in the second analysis carried out with the (TFwAF-02) model, the largest displacement is calculated as Δx = 63.01 mm. According to these results, 3 times larger displacement is calculated with the numerical model, which is thought to reflect the realistic behavior between the timber frame and the adobe filling and uses only link elements that transmit compressive stresses. As can be seen in Figure 6, the diagonal compression block is seen from the upper left corner to the lower right corner of the frame according to the loading direction. According to these results, it can be said that the regions with tensile stress in the infill adobe walls do not contribute to the horizontal stiffness of the timber frame.

Modeling an entire traditional timber building with T/C friction isolator elements in a way that can give necessary accurate results can create some difficulties and problems. These can be listed as errors that may occur during numerical modeling, non-linear elastic static analyzes will not give adequate results due to the use of a large number of connection elements, a discontinuity that cannot be determined in the numerical model, or an error that will affect the analysis results. It can also be added that such analysis takes a very long time depending on the hardware of the computer to be used.

With a simplified structural analysis method and numerical modeling technique to be developed by considering the ratio of the displacements obtained, the results that can give overall information about the structural capacity of the building can be reached while starting the conservation-strengthening planning. Instead of using many non-linear elastic LINK elements to define the infill adobe walls interaction with the timber frame, two T/C friction isolator elements to be diagonally connected from the corners of the frame are prepared (TFwAF-04). However, to define the compressive stiffness of the diagonal T/C friction isolator used in this new model, two separate numerical models have been created.

As shown in Figures 7a and b, as a result of the second analysis, a third analysis is carried out with a new numerical model prepared by taking into account the approximate limits of the compression zone in the infill adobe walls, where only the infill elements are located in the diagonal region (TFwAF-03). In this analysis, the displacements obtained as a result of the second analysis (TFwAF-02) are applied instead of the forces applied to the corner point of the frame. In this way, the stiffness of the two diagonal T/C friction isolator elements to be used in the numerical model with the larger compressive stresses (TFwAF-04) in the infill elements at the diagonal region is approximately determined. Numerical models are shown in Figure 7a (TFwAF-03) and Figure 7b (TFwAF-04).

As summarized in Table 2, the displacements obtained as a result of parametric analyzes, which describe the behavior of the structure in the simplest manner in general, confirm the availability of the proposed simplified structural analysis method. At the connections of the wooden frames, the displacements obtained with the second and

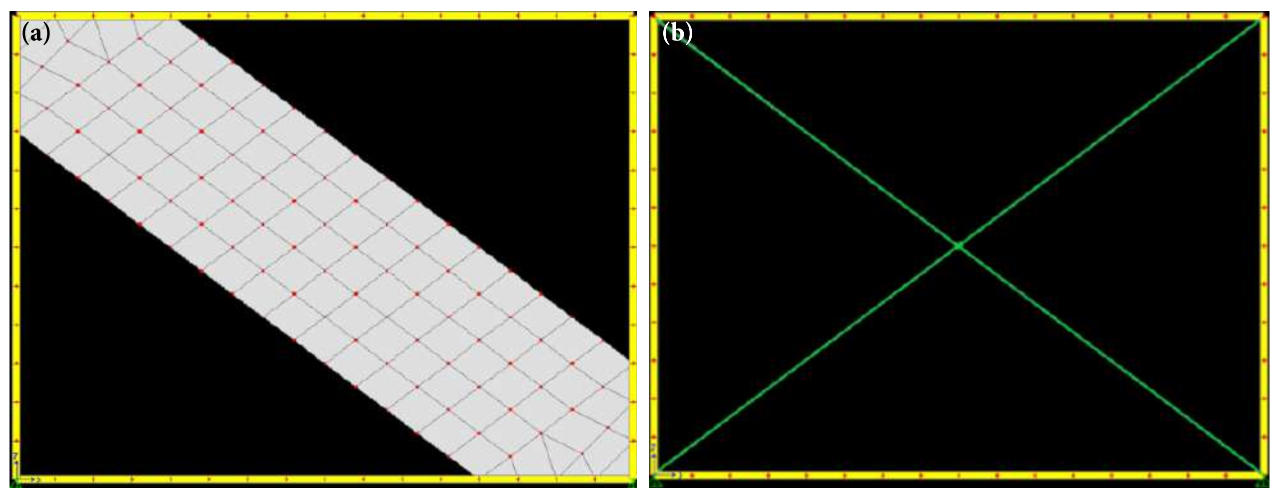

Figure 7. **(a)** (TFwAF-03) numerical model **(b)** (TFwAF-04) numerical model.

third analysis model, which are considered to show more realistic behavior than the applied force, and the fourth analysis model, which is proposed as the simplified analysis method, are quite close to each other. On the other hand, almost 3 times less displacement is calculated in the first analysis model, which is known not to exhibit a true behavior for infill adobe elements. Although it will not fully determine the actual structural behavior of such structures, the moments obtained in the corners where the beam, posts, and infill adobe walls are defined by tensile stress according to the loading direction also provide an idea about the convenience of the simplified analysis method proposed to some extent. As shown in Table 2, the moments found as a result of the second and third analysis and the simplified method, which are thought to be more realistic, are consistent.

APPLICATION OF THE SIMPLIFIED STRUCTURAL ANALYSIS METHOD IN A CASE BUILDING

The simplified structural analysis method is applied to Mehmet Kaya House which is one of the civil architecture examples in the Boyabat district of Sinop province in the Western Black Sea Region. The district has timber-framed masonry houses that are compitable with geographical location, climate, and physical development. The buildings are generally constructed as timber infill adobe or timber bracing frame structures over a masonry stone foundation. Many examples of civil architecture in Boyabat have been inherited from the Ottoman Empire, and some of them were destroyed in the earthquake that occurred in 1943. Today, it is dangerous and forbidden to enter the building. For this reason, floor plans and images could not be taken. The survey of the building was made by Architect Hasan, Gömeç in 2005. In Figure 8, all floor plans of the building are given. Figure 9, 10 and 11 shows the west, north and south facades respectively, nevertheless the east facade cannot be documented due to cuurent condition. It is known that Mehmet Kaya House was built as a timber infill adobe framed structure and is located in the Camikebir neighborhood in Telgrafçı Street (block no: 131, plot no: 2). The building is one of the traditional architectural examples that have survived to the present day.

Since the main purpose of these analyses is to apply the simplified structural analysis method on a traditional timber building, the material, construction, and structural system of the sample building is not taken into account in all details. In the numerical model prepared for simplified analysis, timber

Table 2. Displacements and moments calculated in consecutive analyses

Numerical model used for calculations	Horizontal displacements and position in frames, Δx (mm)				Moments at corner points of the frame (kN·m)
	1	2	3	4	
TFwAF-01	22.15	19.82	10.35	10.10	13.15
TFwAF-02	63.01	62.76	20.48	32.02	23.71
TFwAF-03	66.10	65.35	35.23	30.21	23.46
TFwAF-04	60.80	60.65	30.22	30.14	22.17

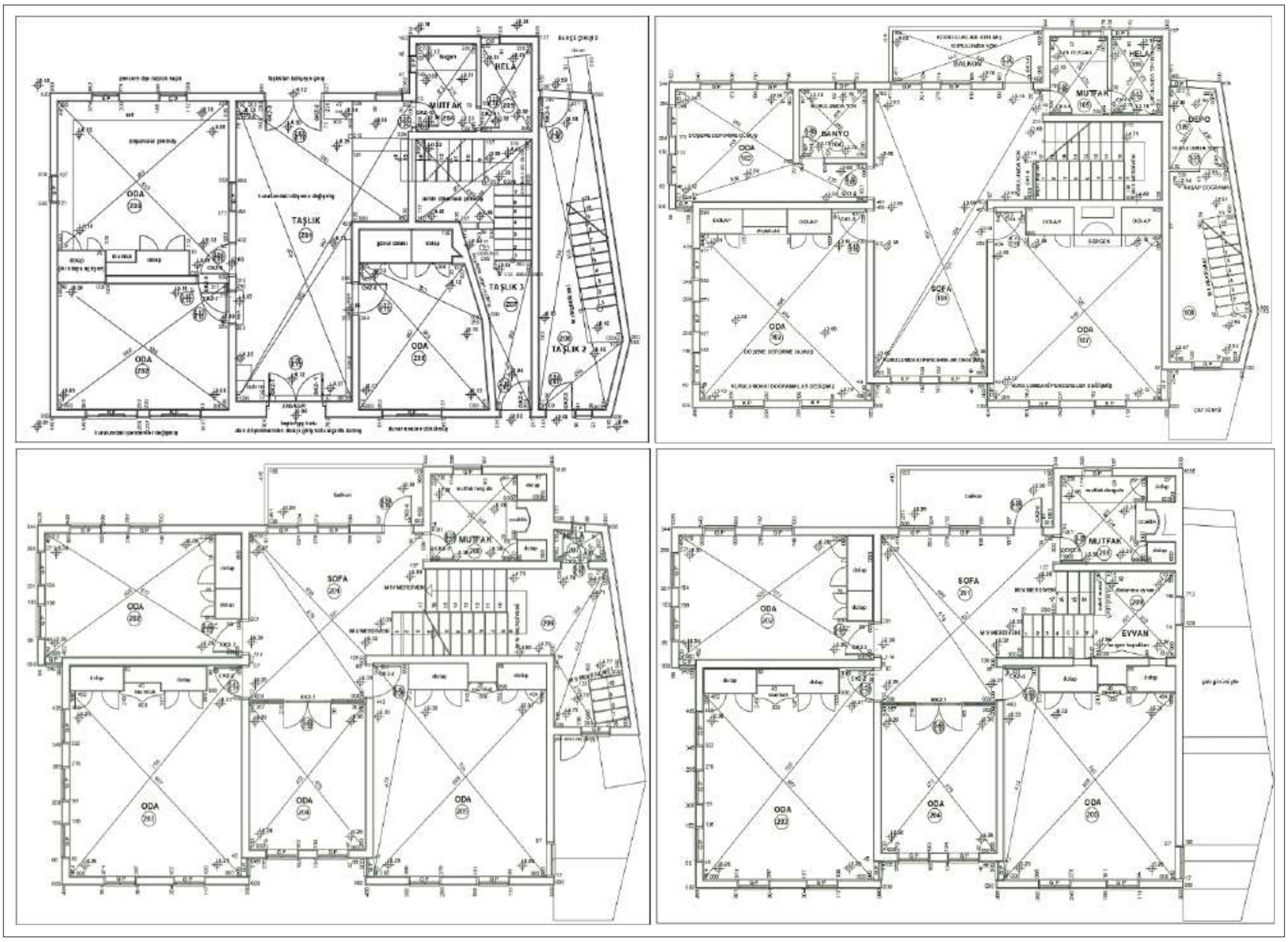

Figure 8. Surveying plans of the ground floor, first floor, second floor, and second iwan floor, respectively.

beams and posts, which constitute the main structural frame of the building, are created. Although the cross-sectional dimensions of the timber posts and timber beams in the existing building are different, in the numerical model, members with an average 200 mm × 200 mm square cross section, are used. As shown in Figure 12, the frame openings between the beams and the posts (infill adobe walls in the existing building) are connected diagonally from the corner joints by T/C friction isolator elements. As explained in the previous section, it is assumed that T/C friction isolator

Figure 9. West facade of Mehmet Kaya House.

Figure 10. North facade of Mehmet Kaya House.

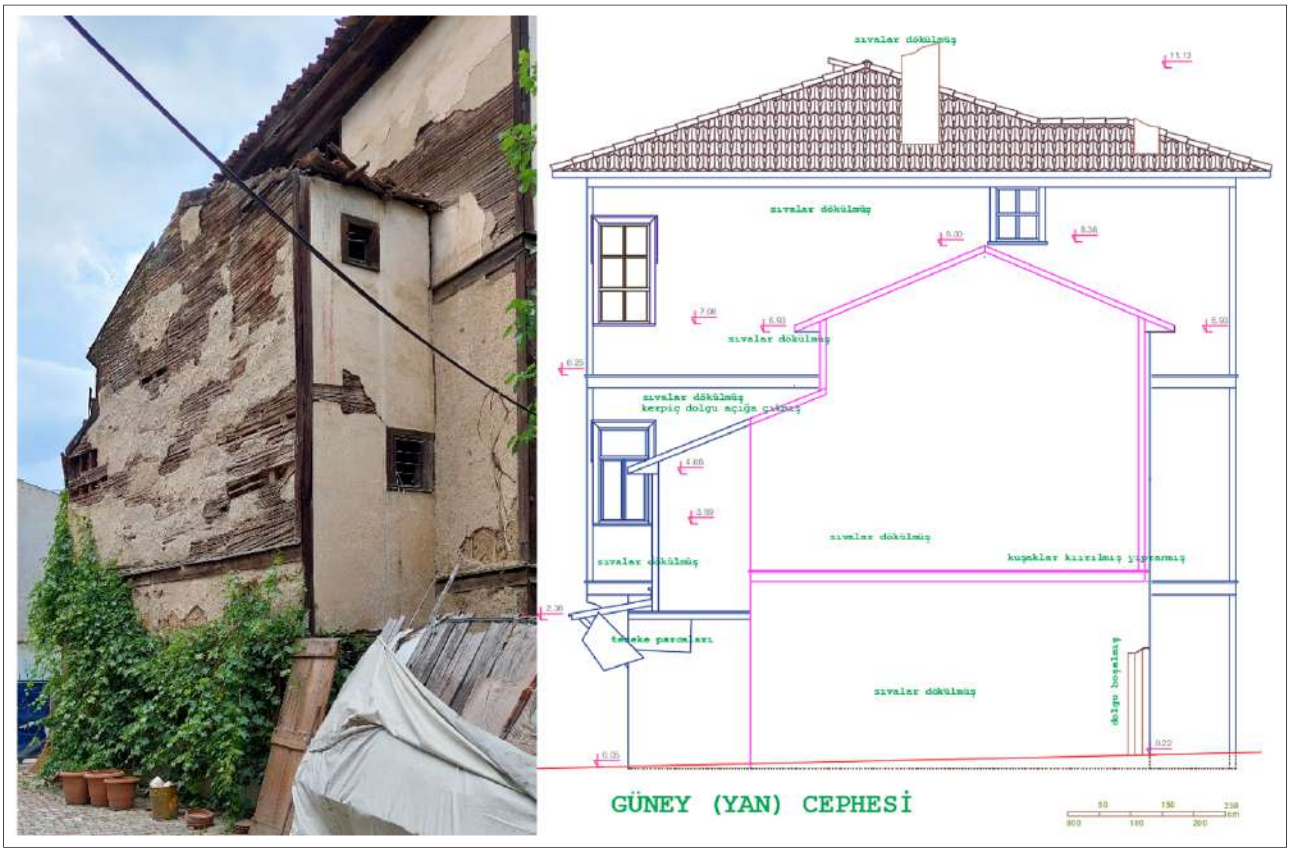

Figure 11. South facade of Mehmet Kaya House.

elements transmit compressive stresses, similar to adobe infill walls, by simply assigning only compression stiffness in their material properties definition.

Since the main purpose of the proposed simplified structural analysis method is to obtain a general idea about the structural behavior of the structure, it should be noted

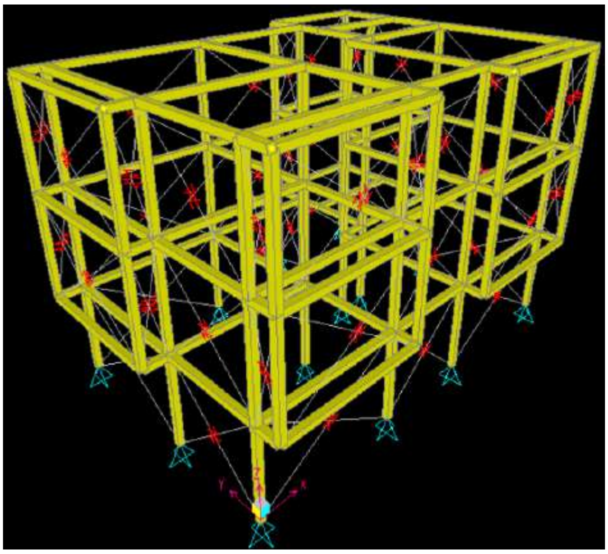

Figure 12. Analytical model of simplified analysis with T/C friction isolator elements.

that the analysis results (displacements, internal forces, and stresses in the structural members) will not serve as an example for the actual structural performance of the building. However, within the scope of the case study, selected support reactions internal forces and bending moments are given in Table 5. Therefore, the compressive rigidity of the T/C isolator elements can be approximately defined according to the position, geometric dimensions, and shape of the infill adobe walls in the numerical model. As in Half Timbered or Bağdadi structures, the effect of cross and horizontal timber members on increasing the strength of infill adobe walls or the effect of window or door openings on reducing the strength of infill adobe walls are some of the factors to be considered when defining the rigidity of T/C isolator elements.

In the previous section, it was stated that the stiffness of T/C friction isolator elements can be approximately determined in the numerical models (TFwAF-03) and (TFwAF-04), which are proposed as simplified structural analysis methods. In the (TFwAF-03) analysis, the stiffness of the diagonal adobe compression block was approximately calculated, and the stiffness of the T/C friction isolator element defined in the (TFwAF-04) analysis is determined. When using the simplified structural analysis method in traditional timber buildings, the dimensions of the infill adobe walls and the stiffness of the T/C friction isolator elements can be expected according to the estimated modulus of elasticity of the infill adobe material. It can be accepted that the compressive rigidity of the T/C friction isolator element is between 10000 kN/m and 15000 kN/m considering the examples based on field observations. As explained earlier, since the purpose of the simplified analysis method is to determine the structural behavior of the building according to the relative displacements under the applied loads, the rigidity of the T/C friction isolator elements can be defined according to the trial and error method.

Traditional timber buildings exhibit stable structural behavior for many years under their weight and other permanent vertical loads. The original structural system of the building is already designed according to the effect of these vertical loads. However, changes in soil conditions due to excavation or drainage works carried out in the vicinity of the building for any reason, deterioration in the main structural elements or infill adobe walls, earthquake, and excessive wind forces are factors that will adversely affect the general structural conditions of the building. In the simplified structural analysis method proposed in this study, instead of defining these loads in detail according to the location and general conditions of the structure, three separate load cases are applied that would determine the overall structural behavior of the building with acceptable accuracy. The first load case is the vertical loads that include the own weight of all the stationary components of the building. The second and third load cases are the gravity loads that consist of 40% of the total weight of the building in the global X and global Y axes, respectively, as the horizontal loads. This is a loading practice generally used in approximate earthquake analysis.

In Boyabat Mehmet Kaya House analysis, according to the window openings, wall thickness and location of the diagonal timber elements of the infill adobe walls, compressive stiffness of T/C friction isolator elements are selected in three different categories, k_{comp1}= 10000 kN/m, k_{comp2}= 12500 kN/m, k_{comp3}= 15000 kN/m, respectively (Vakıflar Genel Müdürlüğü, 2017; Ahşap Yapıların Hesap ve Yapım Kuralları, 1979; Duman and Ökten, 1988). Three successive analyzes are carried out according to a scenario based on the location of the walls and the damage situation.

The numerical models are prepared with the information obtained from the building survey. The simplified structural analysis method, especially the results that help determine the behavior of the building in terms of displacements were obtained. The displacements obtained at different locations of the building according to the different compressive stiffness values of the T/C friction isolator elements assigned at a certain point of the infill adobe walls are shown in Figure 13, Tables 3 and 4.

As a result of the analyses, since the highest forces are observed in the support reactions at the corners of the building, the selected support reactions are shown in Figure 14. As shown in Figure 14, R1 represents the location of the support reaction numbered 1, and red circle number 1 represents the member numbered 1. Support reactions and members are shown, respectively. The support reactions in X and Y directions, shear force, and bending moments

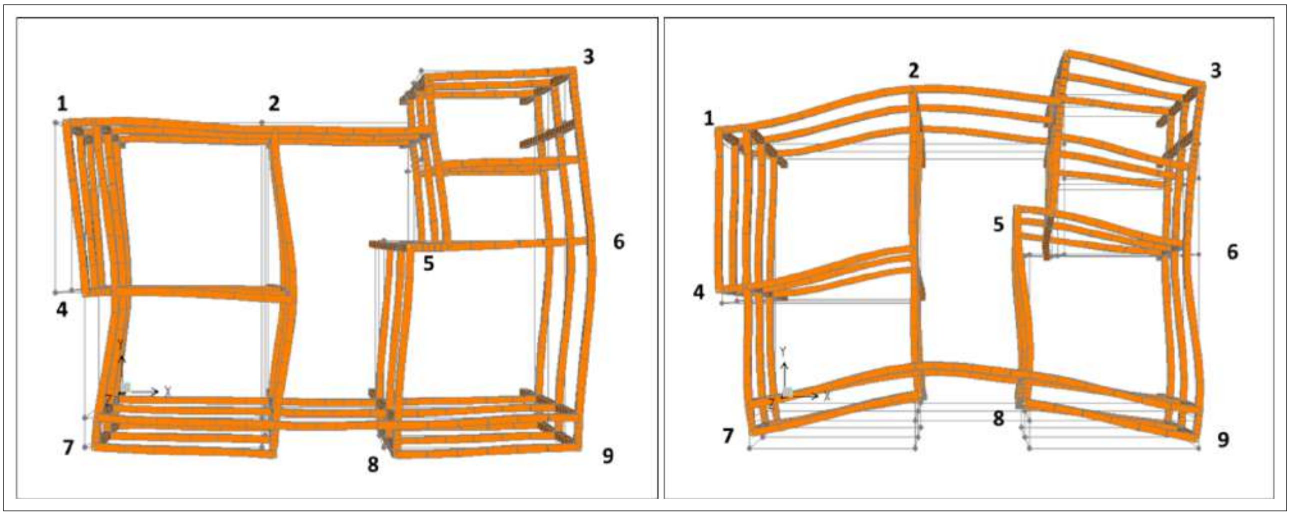

Figure 13. The locations of the points for the measured displacements along X-axis and Y-axis.

Table 3. Displacements at selected locations due to successive analyses

Joint location	Load case	Analysis 1		Analysis 2		Analysis 3	
		Δx (mm)	Δy (mm)	Δx (mm)	Δy (mm)	Δx (mm)	Δy (mm)
1	Case 2 (X)	15.86	−1.18	17.86	−1.22	21.31	−0.87
	Case 3 (Y)	−3.12	15.60	−3.32	15.58	−4.50	20.02
2	Case 2 (X)	12.81	−6.09	17.94	−9.81	21.42	−10.01
	Case 3 (Y)	−4.43	79.06	−4.68	79.16	−4.38	83.41
3	Case 2 (X)	9.69	0.41	10.87	0.47	14.48	0.30
	Case 3 (Y)	4.98	15.29	4.83	15.28	6.46	18.50
4	Case 2 (X)	35.00	−1.32	44.12	−113	45.59	−0.78
	Case 3 (Y)	−5.75	15.35	−3.09	19.67	−3.37	19.96
5	Case 2 (X)	35.62	−9.41	37.88	−9.85	40.40	−970
	Case 3 (Y)	−17.35	66.47	−17.59	66.56	−18.64	73.12
6	Case 2 (X)	35.61	0.36	37.87	0.41	40.38	0.24
	Case 3 (Y)	−17.35	15.17	−17.59	15.16	−15.05	14.57
7	Case 2 (X)	14.50	1.10	16.84	1.08	16.99	1.18
	Case 3 (Y)	5.08	17.39	5.48	23.23	5.48	17.68
8	Case 2 (X)	17.43	−0.94	19.85	−9.80	20.00	−9.66
	Case 3 (Y)	−4.91	54.35	−4.99	54.40	−5.41	73.25
9	Case 2 (X)	17.51	0.26	19.92	0.31	20.07	0.14
	Case 3 (Y)	−4.97	15.06	−5.08	15.05	−5.26	14.10

Table 4. Displacements along the first to third floor levels due to successive analyses

Floor Level	Displacements along in X-axis			Displacements along in Y-axis		
	Analysis 1 Δx (mm)	Analysis 2 Δx (mm)	Analysis 3 Δx (mm)	Analysis 1 Δy (mm)	Analysis 2 Δy (mm)	Analysis 3 Δy (mm)
3	41.87	44.08	45.55	−9.42	−9.81	−10.01
2	35.01	36.76	37.84	−6.08	−6.08	−6.59
1	25.12	25.26	26.85	−3.45	−3.45	−3.83

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Table 5. Support reaction, Shear force, and bending moments at selected members on the third floor due to successive analyses

Joint location	Selected Member	Load Case	Analysis 1				Analysis 2				Analysis 3			
			Rx (kN)	Ry (kN)	V (kN)	M (kN·m)	Rx (kN)	Ry (kN)	V (kN)	M (kN·m)	Rx (kN)	Ry (kN)	V (kN)	M (kN·m)
R1	1	LC2 X	−0.47	0.03	0.36	0.18	−0.55	0.04	0.45	0.33	−0.69	0.03	0.54	0.47
		LC3 Y	12.46	−84.9	0.67	1.11	11.25	−84.9	0.68	1.13	8.7	−86.3	0.71	1.18
R2	2	LC2 X	−66.9	0.22	0.76	0.86	−65.5	0.23	0.83	1.0	−65.4	0.25	0.95	1.26
		LC3 Y	0.52	−4.39	0.11	0.21	1.15	−4.39	0.12	0.22	1.68	−4.65	0.13	0.24
R3	3	LC2 X	−32.1	−1.46	0.42	0.28	−36.1	−1.95	0.43	0.29	−35.3	−1.05	0.5	0.44
		LC3 Y	−25.4	−18.1	0.15	0.29	−24.9	−18.1	0.14	0.29	−22.6	−15.5	0.16	0.34
R4	4	LC2 X	−2.57	0.04	0.79	0.92	−2.66	0.04	0.82	0.95	−2.69	0.03	0.85	1.01
		LC3 Y	1.43	−57.7	0.71	1.24	1.44	−57.7	0.71	1.23	1.49	−58.7	0.72	1.26
R5	5	LC2 X	−2.33	0.38	1.42	2.09	−2.41	0.4	1.5	2.24	−2.45	0.42	1.56	2.36
		LC3 Y	0.91	−5.53	0.51	1.01	0.91	−5.53	0.58	1.0	0.95	−5.85	0.51	1.01
R6	6	LC2 X	−2.17	−6.49	0.87	1.15	−2.27	−6.79	0.92	1.26	−2.38	−6.77	0.97	1.37
		LC3 Y	0.69	−59.4	0.59	1.13	0.7	−59.4	0.6	1.14	0.8	−74.1	0.6	1.16
R7	7	LC2 X	−0.33	2.22	0.44	0.34	−0.41	2.55	0.47	0.42	−0.4	1.76	0.47	0.41
		LC3 Y	3.45	−0.22	0.01	0.01	3.39	−0.22	0.01	0.01	3.36	−0.22	0.01	0.01
R8	8	LC2 X	−61.2	0.05	0.47	0.39	−61.5	0.06	0.5	0.49	−62.4	0.08	0.51	0.49
		LC3 Y	3.6	−5.31	0.01	0.02	3.37	−5.31	0.02	0.04	3.34	−5.62	0.02	0.04
R9	9	LC2 X	−72.5	−0.35	0.06	0.39	−71.3	−0.36	0.5	0.48	−71.2	−0.37	0.5	0.48
		LC3 Y	0.03	−0.27	0.05	0.08	0.03	−0.28	0.05	0.1	0.03	−0.35	0.05	0.09

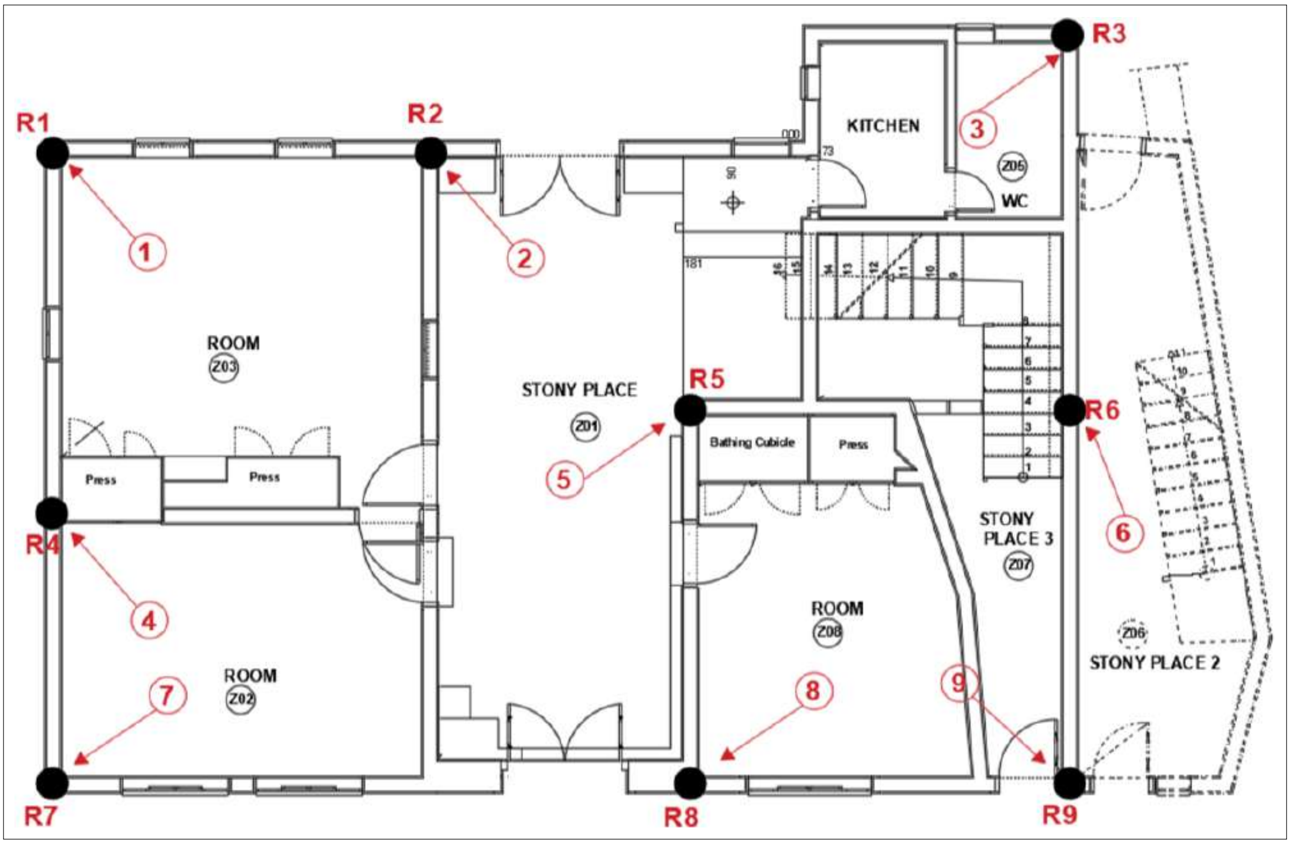

Figure 14. The locations of selected support reactions and selected members on the third floor.

at selected members on the third floor due to successive analyses are given in Table 5.

In the first analysis, the compressive stiffness of the T/C friction isolator element is selected as k_{comp3} = 15000 kN/m, assuming that all the infill adobe walls were in very good condition and the window and door openings were ignored. In the second analysis, the compressive rigidity is selected as k_{comp2} = 12500 kN/m of the T/C friction isolator element in the places where there are doors and windows. In the third analysis, the compressive stiffness of the T/C friction isolator element in the places where the material deterioration is effective and the infill adobe walls are observed in places are selected as k_{comp1}= 10000 kN/m (Vakıflar Genel Müdürlüğü, 2017; Ahşap Yapıların Hesap ve Yapım Kuralları 1979; Duman and Ökten, 1988). Displacements at various selected points of the building show significant results about the structural behavior of the building according to the compressive stiffness of the T/C friction isolators, as can be seen in the tables where the results are summarized and Figure 12. At the same time, significant changes in internal forces, which are calculated in proportion to displacements in the beams and posts of the building, also enable the monitoring and evaluation of the structural behavior of the building.

RESULTS AND DISCUSSION

First, a plane frame numerical model is prepared for these analyses. It has been assumed that the adobe intermediate element behaves wholly with the first model TFwAF-01 timber frame system prepared for easier understanding of displacements. TFwAF-02 T/C friction isolator element that transmits compressive forces that do not transmit tensile forces is defined on adobe and timber frame interface. According to the results of these analyzes, the displacement of the numerical model TFwAF-02 (Δx = 63.01mm), which is thought to reflect the realistic behavior between the timber frame and the infill adobe walls which uses only link elements that transmit compressive stresses, is 3 times larger than the displacement of the TFwAF-01 (Δx= 22.15mm) model.

Numerical models TFwAF-03 and TFwAF-04 have been prepared to be diagonally connected T/C friction isolator elements from the corners of the timber frame. In the TFwAF-03 model, the displacements obtained as a result of the second analysis (TFwAF-02) were applied instead of the forces applied to the corner point of the frame. Thus, the stiffness of the two diagonal T/C friction isolators to be used in the TFwAF-04 numerical model was approximately determined with the larger compressive stress in the infill adobe walls in the diagonal region. At the junctions of the modeled frame, the displacements obtained in the TFwAF-04 analysis model, which is accepted to show more realistic behavior than the applied force, and the TFwAF-03 analysis model, which is proposed as a simplified analysis method, are quite close to each other. Although it will not fully determine the actual structural behavior of such structures, the moments obtained in the corners where the beam, posts, and infill adobe walls are defined by tensile stress according to the loading direction also indicate an idea about the convenience of the simplified structural analysis method proposed to some extent.

The results of simplified calculation method and the experimental studies were similar. T/C isolators used at the connection points have verified the displacement-compression stiffness of timber frames with adobe fill walls within the framework of engineering principles. The structural behavior of timber frames with adobe or stone fill walls in experimental and numerical studies is consistent with the simplified calculation scenarios. In the seismic capacity assessment of the adobe structure, Aguilar et al. (2019) showed that the compressive-tensile stresses at the connection points were weak against the earthquake loads of the case studies. Sandak et al. (2019) showed that the first local displacement was 7 mm and the displacement was 60-80 mm in the subsequent cyclic loadings in the experimental studies with timber-framed stone infill walls. In the simplified calculation model, which has similar characteristics with these studies, the displacement of the TFwAF-02 (Δx =63.01 mm) model was found to be within the limits of agreement with TfwAF-01 (Δx=22.15 mm) (stone-brick infill difference). Dutu (2021), on the other hand, has shown that timber diagonal frame members are significantly effective in preventing lateral displacements Similar results were obtained by defining adobe infill walls with different stiffness coefficients in numerical modeling. With the simplified calculation method, the structural behavior can be easily interpreted by every professional. For this reason, the simplified calculation method can be considered as feasible in terms of time, cost, and labor savings.

CONCLUSION

Interdisciplinary approaches are needed for the conservation and restoration of historical buildings. Ensuring the stability of the structure can be managed primarily by interpreting the building correctly. The structural analysis of traditional timber buildings differs from the analysis approaches of today's modern structures. In the analysis of a traditional timber building, criteria such as member sizes of frame systems, connection details, and material properties of unit elements may not be analyzed with a simple approach as the systems used in modern structures. Therefore, it is necessary to develop a simplified calculation method to reach the closest results in the conservation and strengthening works of traditional timber buildings.

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