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STRUCTURAL CONSIDERATIONS FOR THE USE OF MASONRY AS AN EFFICIENT CONSTRUCTION METHOD

Dr. Özgür BEZGİN[1], Ümit ÖZKAN[2], Dr. Murat ŞENER[3], Orhan MANZAK[4]

Abstract:

Structural requirements of a building are determined by the loads and the ambient structural effects that the building is expected to be exposed to. Functional requirements of a building are determined by the habitation and the efficiency conditions that the building is designed for. The weight of a building is distributed among its structural system and its functional system. The materials used in the construction of the functional system which has to satisfy architectural and isolation requirements, have random and structurally unaccounted inherent mechanical properties and high dead weight that create a burden on the engineered structural system of a building. The results of seismic events in Turkey indicate that the functional system of buildings may have a negative interference with the structural system of the buildings. Thus the separation of the two systems within a building results in increased weight and reduced structural performance. Reinforced masonry construction is a sustainable and an efficient construction method that has the potential to satisfy the structural and functional requirements of a building within a single system.

This paper introduces the concept of combining the structural system of a building with its functional system and highlights the advantages of the use of reinforced masonry for the structural system of a building. UBC Masonry design guidelines are introduced through "Arkeon Evleri" Project.

Keywords:

Masonry, lateral loads, shear wall, diaphragm, functionality

[1] Yapı Merkezi Prefabrication Inc., 34935 Istanbul, Turkey, ozgur.bezgin@ym.com.tr
[2] Yapı Merkezi Prefabrication Inc., 34935 Istanbul, Turkey, umit.ozkan@ym.com.tr
[3] Yapı Merkezi Prefabrication Inc., 34935, Istanbul, Turkey, murat.sener@ym.com.tr
[4] Yapı Merkezi Prefabrication Inc., 34935, Istanbul, Turkey, orhan.manzak@ym.com.tr

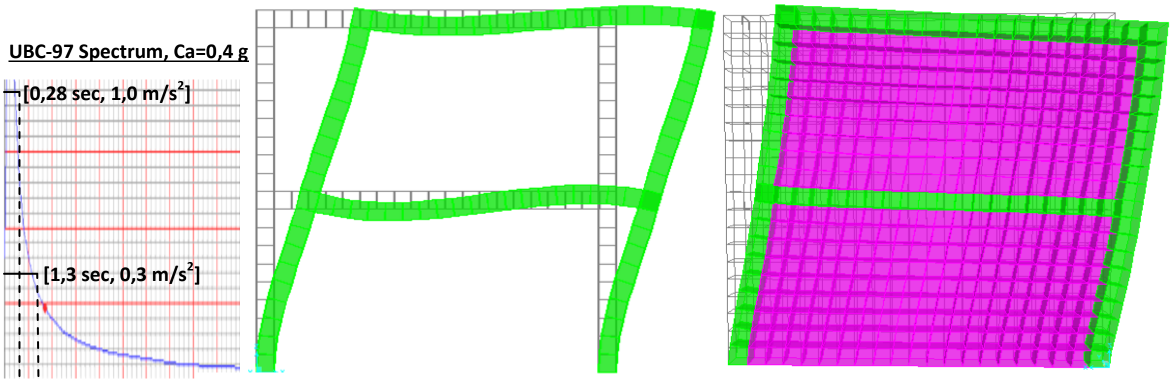
1. INTRODUCTION

Design and construction of a building is a consequence of a functional need. The architectural solution to a functional need is made a reality by the engineering solution of a structural system. Construction of a building not only involves the engineering of the load bearing elements within the structure but also involves incorporating within this structural system, a functional system that would create a habitable environment within the building.

Construction of a building is a sequence of events that require time and effort. The initial step of the construction process is the selection of engineered materials which is later given a structural formation within the boundaries required by architecture. This formation gives the necessary structural frame within which the functional components of the building can be incorporated that leads to the completion of the building. It would be desirable to have a building the weight of which is completely structural; however in reality, only a percentage of this weight belongs to the structure of the building.

2. UNDETERMINED INFLUENCES ON ENGINEERED STRUCTURES

Functional components of a building have inherent mechanical properties that are typically considered non-structural and are not included in the structural design of a building. This non-structural weight is not only a burden on the structure of the building but also has an undetermined influence on the engineered-structure of the building due to its inherent mechanical properties. As an example of what kind of an effect the functional components of a building could have on the structural mechanism of a building, let’s consider construction with reinforced concrete that typically involves the formation of a concrete frame, which is later filled with bricks to form façade and interior walls. Two, 2-storey 5m x 5 m concrete frames are constructed from C30 concrete with 25cm x 25cm beams and columns. One of the concrete frames is filled with hollow clay bricks and both frames are analyzed under UBC-97 response spectrum which is shown on the left hand side of figure 1. The deflected shapes of the frames are shown in figure 1 to the same scale. The material properties of the materials effective on the dynamic response are for concrete: M_c = 2.500 kg/m^3 and E_c = 32.000 MPa and for hollow-clay bricks: M_b = 1500 kg/m^3 and E_b = 14.000 MPa. This simple analytical study is an indicator of the structural influence of a functional component on the engineered structure of a building. The wall not only increases the loads on the frame but also prevents the frame from reacting since it prevents the frame from deflecting. Here it is seen that, the rigidity of the structure increases and its natural period decreases. This decrease in the natural period results in increased accelerations and also increases the axial loads and shear on the columns. As a result, the influence of non-structural components on the behavior of a structure could lead to reactions much higher than originally anticipated. The intention to develop a construction concept for a building that would attempt to resolve the functional design of a building within its structural system would therefore be justified.



- Mod.1
- T=1,3 sec
- A(T)= 0,3 m/s^2
- Axial force= 1949 kg
- Shear force= 158 kg

- Mod.1
- T=0,28 sec
- A(T)= 1,0 m/s^2
- Axial force= 9583 kg
- Shear force= 745 kg

Figure 1 – Displaced shapes of a concrete frame.

3. QUALITATIVE UNDERSTANDING OF MASONRY STRUCTURES

Masonry construction, which involves the formation of a structure by the repeated use of masonry units with or without the use of steel reinforcement, has the advantage of simultaneously providing the functional surfaces of the building as well as its structural system. ‘Figure 2’ shows only some of the many examples of masonry units. An inherent advantage of masonry construction is that the masonry units can be engineered to many sizes and forms to answer the structural need.

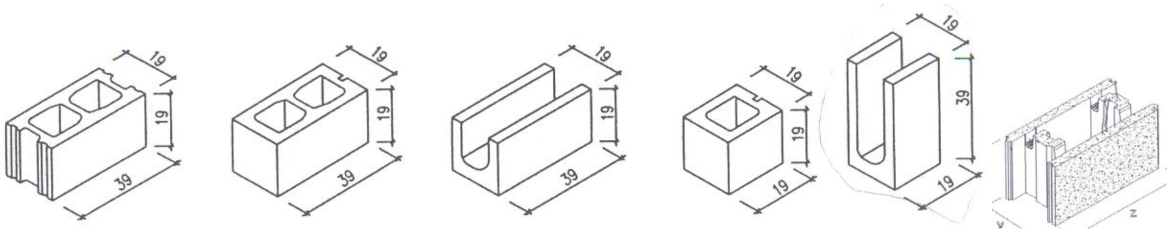


Figure 2 – Typical examples of masonry units.

Masonry provides compressive resistance, stability, weathering durability, energy efficiency, and fire protection to the building and it can be used for load bearing and non-load bearing external and internal walls, retaining walls, chimneys, elevator shafts and staircase shafts. The surfaces formed by the repeated use of these units not only serve as the architectural skin of the building but also provide an important part of the functional design of the building such as its thermal and acoustic insulation. Masonry construction eliminates the need for formwork which is necessary in concrete construction, since the cellular masonry units themselves provide the necessary forms in which grout can be poured. Masonry construction also eliminates the need for plastering and architectural surfacing, since the masonry units can be supplied in the required architectural texture and colour.

Early masonry construction where steel reinforcement was not used relied only on the compressive strength and the stability provided by the weight of the materials used. *Monadnock Building*; a 16-storey brick-bearing wall structure built in Chicago during 1889-1891, had a wall thickness of 1.5 meters at the base of the building to provide the required strength and stability.

Figure 3 – Monadnock building constructed in 1891.

Such method of masonry construction by excessive use of material proved un-economic and also resulted in increased lateral loads on the structure in seismic regions and forced engineers to develop a composite design methodology by the use of steel reinforcement. Therefore, use of plain masonry developed into reinforced masonry.

'Figure 4' shows masonry construction as a structural system which involves the distribution of load bearing walls with high flexural and shear stiffness around the perimeter of floor areas to create a shear-wall system [Schneider and Dickey,1988]. The floors are used as diaphragms that distribute the lateral forces to the reinforced masonry walls which provide the required shear resistance as well as the support for the vertical loads. A reinforced masonry shear wall is a deep beam. By resisting the in-plane shear and bending moments caused by the horizontal force brought to it by a floor or roof diaphragm, it imparts lateral stability to the structure. This element also functions as a bearing wall which is subjected to vertical compressive stresses.

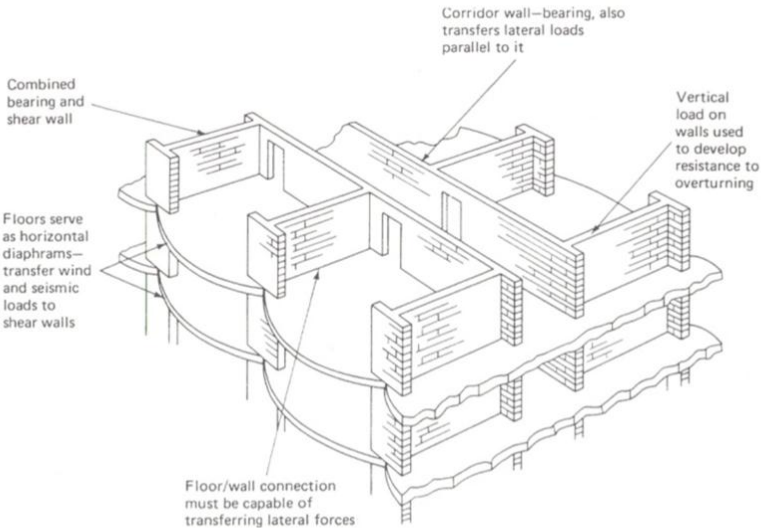


Figure 4 – Structural characteristics of masonry construction.

4. STRUCTURAL ASPECTS OF MASONRY CONSTRUCTION

The hollow masonry units can be laid in many patterns, as shown in 'Fig. 5'. A commonly used pattern is the "running bond" system, where a masonry unit overlaps with two other units below and above. Once the wall is constructed, it is grouted and reinforced vertically and horizontally at certain intervals depending on the design requirements. The end result is a load bearing wall with functional characteristics. The structure shown in 'Fig. 5' could also be viewed as a structure where the beams and columns are hidden within the walls.

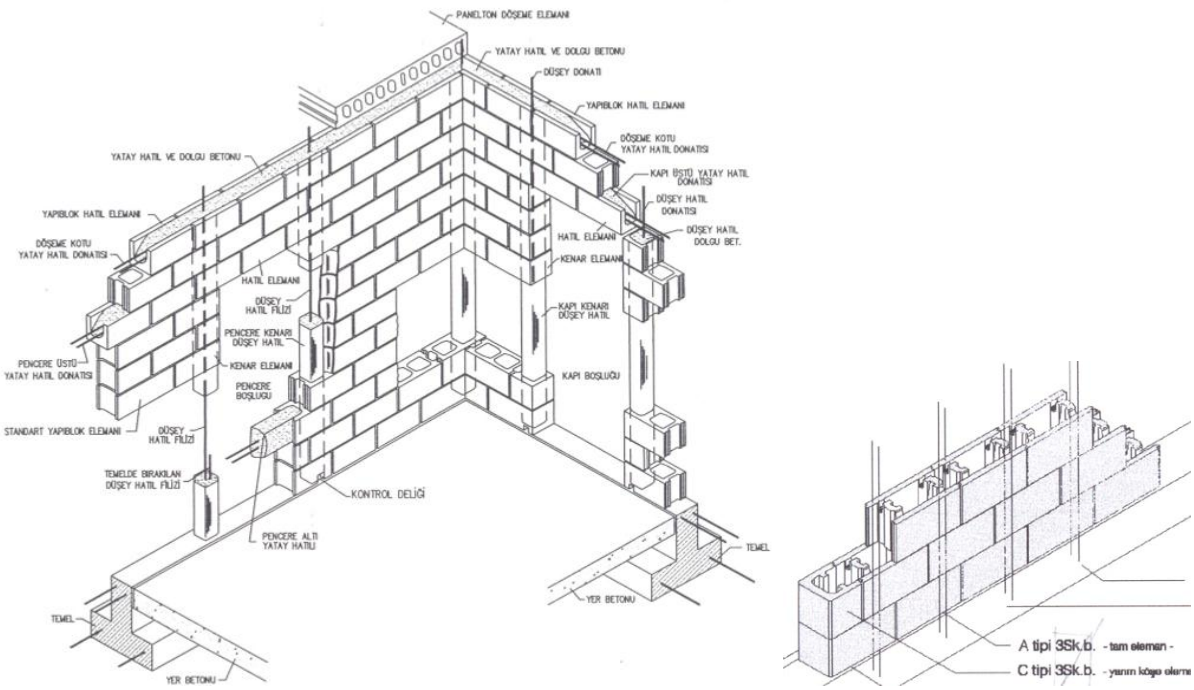


Figure 5 – Structural elements within precast masonry construction.

If the architecture of the building requires wide openings for windows and doors such that the masonry walls is not sufficient to resist the imposed loads, they can be reinforced by masonry-piers that are embedded within the wall to provide the necessary strength and stiffness. 'Figure 6' shows the formation of such piers within the walls that are formed from unique masonry units.

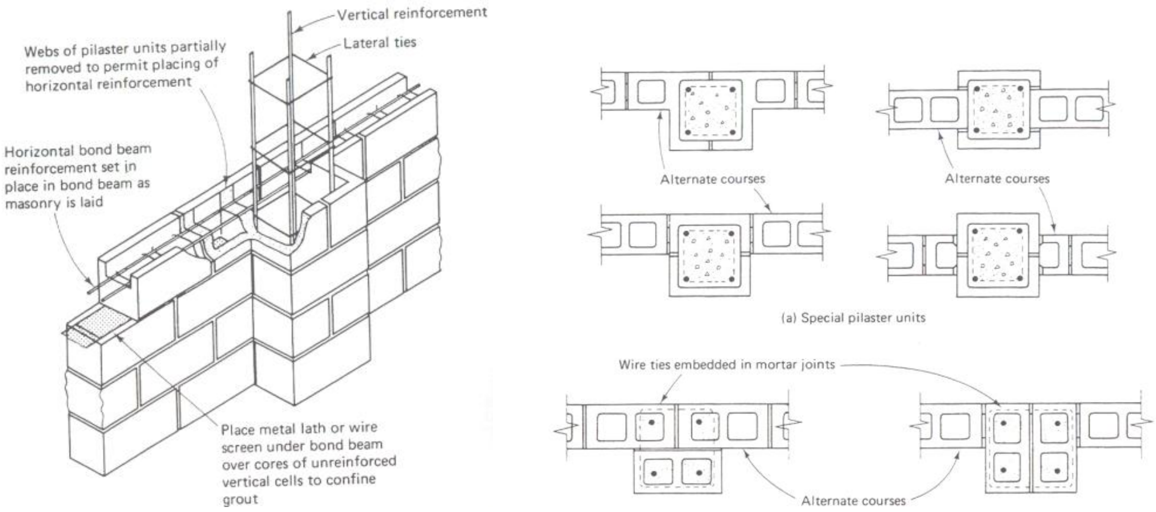


Figure 6 – Use of masonry units to construct piers.

The vertical masonry shear-wall elements support precast or cast-in-place concrete slabs. In "Arkeon Evleri" hollow core precast slabs are used. Following the installation of precast units, the slabs are reinforced and grouted together along the keyways and a structural topping is provided with proper anchorage to the slabs underneath at the keyways. The individual slabs thus formed, constitute a system which behaves similar to a monolithic slab. Once the lateral forces to be applied to the diaphragm are determined, these forces are distributed to the lateral-resisting elements which will carry the forces to the foundation. The problem is a structurally indeterminate problem and the deformation compatibilities must be considered for analysis. Concrete diaphragms are normally considered to be rigid when compared to the lateral-load resisting elements. However there are cases where the diaphragm rigidity is debatable and the diaphragm flexibility must be considered since the distribution of the loads is quite different for the rigid and flexible diaphragm considerations. Lateral forces are brought to the walls on the basis of tributary areas when the diaphragm is flexible and on the basis of relative wall rigidity distribution when the diaphragm is rigid. The rigidity indicates that the diaphragm does not change its plan shape when subjected to lateral loads. A perfect-rigid diaphragm distributes the horizontal forces to the vertical resisting elements in direct proportion to the relative rigidities of those elements and is capable of transferring and redistributing forces through torsion. A perfect-flexible diaphragm is unable to transfer torsion and acts as beams spanning between very rigid supports since the relative stiffness of the non-yielding supports is relatively higher compared to that of the diaphragm. UBC requires consideration of the diaphragm flexibility for the horizontal distribution of forces in seismic regions. A flexible diaphragm is defined by the UBC as one having a maximum lateral deformation more than twice the average storey drift for the level under consideration. Determination of the center of rigidity and the center of mass of the structure based on the known mechanical properties of the materials, the floor plans and the geometric properties of the structural cross-sections are required to distribute the lateral loads to the load bearing elements. As a result of this distribution, the mutual effect of the lateral loads and gravity loads based on the tributary areas of the load bearing elements are thus found.

4.1 Distribution of lateral loads within a structure:

The understanding and design of a structure is the responsibility of the engineer and an understanding of the diaphragm behavior is very important and should be especially questioned under certain conditions that would influence the relative stiffness distribution within a slab-shear wall system such as:

- The spans between the shear walls are large compared to the length of the walls
- The diaphragm thickness is much smaller than the thickness of the supporting walls
- The slenderness of the slab between points of support is high.
- The slenderness of the shear walls is low
- Existence of large gaps in the walls and the slabs
- Difference in the strength of the materials used in the walls and the slabs

Three-dimensional numeric system analysis of shear walls and diaphragms should be conducted under lateral loads to determine the diaphragm behavior whenever there is a question of stiffness distribution within a box-system. One such analysis was conducted for a project where the distribution of the wall rigidities was considered to be uneven and the slabs were considered to be very slender compared to the walls. The investigated storey had 15 cm thick prestressed and pretensioned precast hollow core slabs with 7 cm topping that had an equivalent total prismatic slab depth of 13 cm. The 19cm thick masonry wall system was used around the perimeter and the floor span was 8.8 meters between the 9.2 meter long walls. There were two smaller walls between the perimeter walls with 1.7 meter lengths. The concrete strength was same for the walls and the floor. The resulting box-system had high variations between the wall rigidities and a thin and slender diaphragm compared to the thickness and the slenderness of the walls. Under a lateral load of 0,4g, the storey was first analyzed as a perfect-flexible storey and then a perfect-rigid storey, and finally was analyzed as-is and then compared to the perfect assumptions. ‘Figure 7’ shows the perfect-flexible and three-dimensional solid analysis of the storey under investigation.

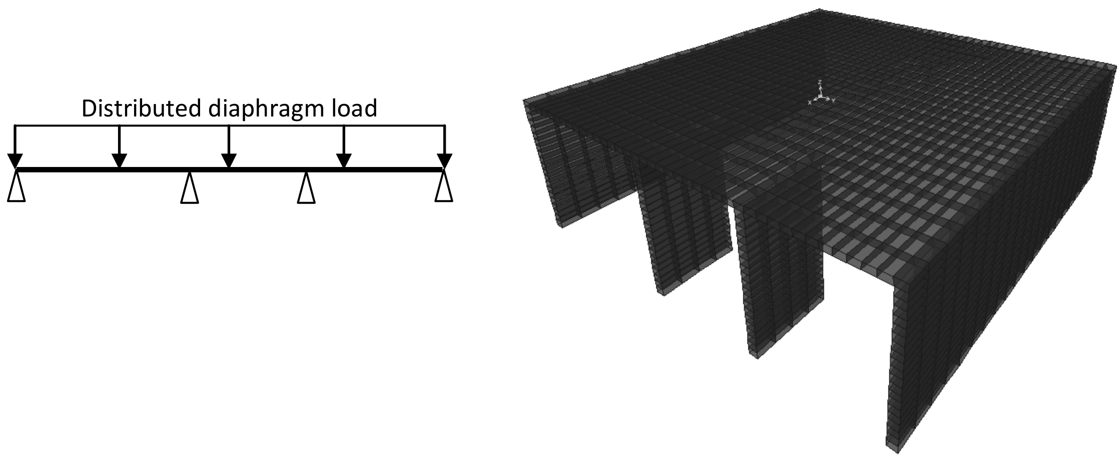


Figure 7- Flexible diaphragm analogy and combined shear wall and diaphragm model.

The relative rigidities of the walls are 12.77 for the side walls (280 cm x 920 cm) and 1.24 for the interior walls (280cm x 170cm). Thus, rigid diaphragm analysis would create approximately ten times more loading on the exterior walls. The distance between the center of rigidity and the center of gravity is 3 cm. The resulting lateral wall reactions are shown in ‘Fig. 8’. If the walls are labeled 1 to 4 from left to right in ‘Fig.7’, it is seen that the flexible interpretation of the diaphragm places the burden on the walls based on the tributary width of the walls and torsion cannot be transferred. The rigid interpretation of the diaphragm places the burden on the walls based on their relative rigidities. The ratio of the maximum diaphragm displacement to the wall displacement was found to be 1.52 which is lower than the UBC criteria. The solid element model of the wall-diaphragm behavior indicates the influence of the flexible-diaphragm effects on the intermediate walls. The burden on the interior walls is approximately doubled where the load on the perimeter walls is reduced approximately 16%. As a result it was decided that the behavior of the diaphragm was much closer to the rigid diaphragm assumption than to the flexible diaphragm assumption. However the minor flexibility that the system had, had an effect on the burden placed on the walls. This effect was more pronounced on the interior walls that had lower relative rigidity and therefore had to be accounted for in the design.

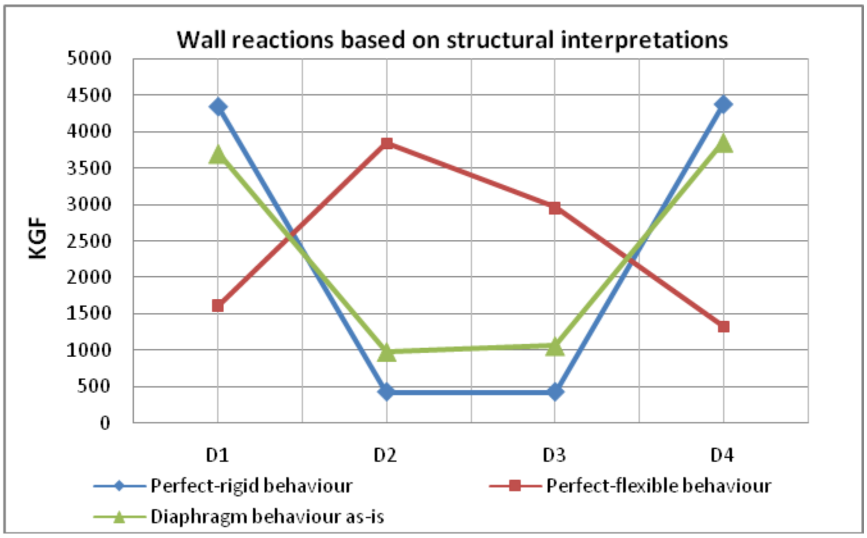


Figure 8 – Distribution of wall reactions based on diaphragm behavior.

To provide the diaphragm with the strength to transfer imposed lateral loads from the point of application to the point of resistance and to satisfy structural integrity, all diaphragms should have boundary elements and collector elements to ensure that a diaphragm will have the strength to transfer lateral loads to the lateral resisting system. ‘Figure 9’ shows typical boundary elements within a diaphragm. Some details for these boundary elements are shown in ‘Fig.10’.

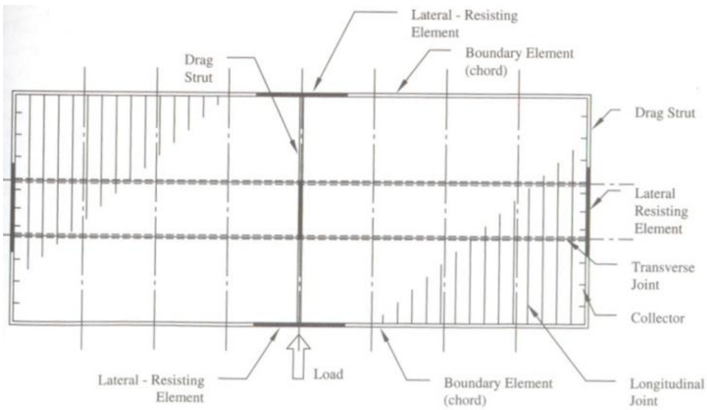


Figure 9 – Boundary elements within a diaphragm.

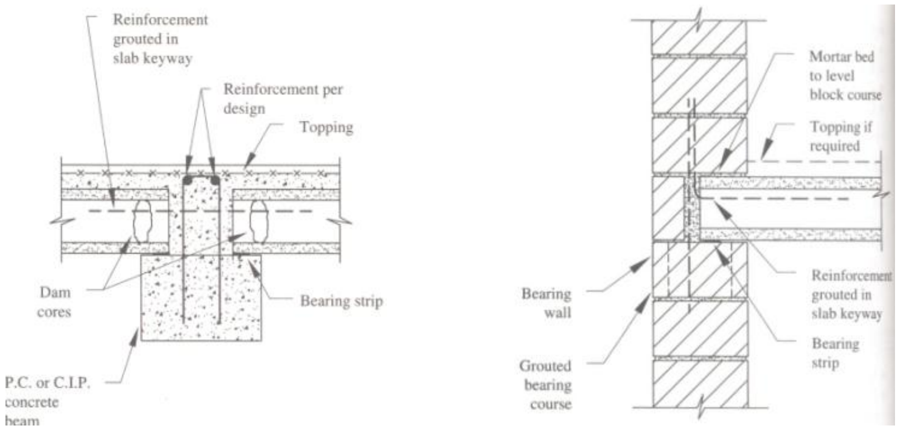


Figure –10 – A detail for collector and chord elements.

The provision for boundary elements is especially important for precast diaphragm construction that involves repeated use of panels that are bound together by CIP concrete. Boundary elements are the chord elements at the tension and compression flanges of the diaphragm and drag strut elements that distribute shear loads over a greater length of the diaphragm. Collector elements are needed to transfer the forces from the diaphragm to the lateral resisting elements or to get the forces into the diaphragm. Boundary elements are used as the load path from the diaphragm into the lateral force resisting system or as stiffness elements within the diaphragm where the continuity of the diaphragm is disturbed to provide access between neighboring floors.

5. A MODERN APPLICATION OF MASONRY CONSTRUCTION

Arkeon Evleri project is comprised of 3-storey houses with a basement and two stories above the ground level. The structures are built with prefabricated structural elements which includes precast hollow core slabs as rigid diaphragms supported by reinforced masonry units as vertical and lateral load bearing wall elements.

Figure 11 – Arkeon Evleri.

The project is situated in a seismic region categorized as Level-1. The following are the design loads:

- Slabs: 0,236 t/m^2
- Slab topping (7cm): 0,168 t/m^2

- Flooring: 0,1 t/m^2
- Architectural wall load: 0,050 t/m^2
- Live load: 0,2 t/m^2
- Balcony and staircase live load: 0,350 t/m^2
- Snow load: 0,075 t/m^2

The seismic analysis of the buildings was based on equivalent lateral load procedure and was based on the following values:

- Spectrum constant: S(T) = 2.5
- System quality factor: R =2.5
- Spectral acceleration constant: A(T)=0.4
- Effective ground acceleration constant: A0=0.4
- Building importance factor: I=1.0

Based on the architectural and structural plans, the vertical loads on the masonry walls were found based on the one-way and two-way action of the slabs. The center of gravity and the center of rigidity location were determined for each storey and the lateral loads were distributed to the supporting masonry walls with openings for doors and windows, through rigid-diaphragm action and detailing was revised by the flexibility considerations for the diaphragm as was shown in section 4.1. Once the lateral loads and the vertical loads were distributed to the vertical load carrying elements, UBC 97, ACI 530-99, ABYYHY 97 codes were used following the allowable stress design procedure for the design of the walls. Based on these codes the design strengths were determined as follows:

- Allowable axial compressive stress: [UBC-97-2107.2.5 and ACI530-05-2.3.3.2.1]

$$F_a = 0.25(f'_m A_n + 0.65 A_{st} F_s)\left[1 - \left(\frac{h}{140r}\right)^2\right] for\ h'/r \leq 99$$

$$F_a = 0.25(f'_m A_n + 0.65 A_{st} F_s)\left(\frac{70r}{h'}\right)^2 for\ h'/r > 99$$

- Allowable flexural compressive stress: [UBC-97-2107.2.6 and ACI530-05-2.2.3]

$$F_b = 0.33 f'_m$$

- Combined compressive stresses: $\frac{f_a}{F_a} + \frac{f_b}{F_b} \leq 1$ [UBC-97-2107.2.7-(7-16)]
- Allowable shear stress: [UBC-97-2107.2.9 and ACI530-05-2.3.5.2.3]

Where shear reinforcement is designed to take the entire shear:

$$F_v = 0.042\left(4 - \frac{M}{Vd}\right)\sqrt{f'_m} \leq 0.82 - 0.31\left(\frac{M}{Vd}\right)\sqrt{f'_m}$$

6. CONCLUSION

Masonry construction provides a reliable solution for urban developments, through which the functional components of a building can be resolved within its engineered structure. Masonry units; combined with other prefabricated components, provides a closed-box form rigid structure within which the architectural elements can be embedded and which can provide the necessary structural stiffness to the building. The relative stiffness distribution between the masonry walls and floor plate defines the lateral load distribution

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