

Reinforced Masonry Design: An Innovative Construction Technique of Earthquake Resistant Structures for Türkiye

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Abstract

The weight of a building is distributed among its structural system and its functional system. 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. In Türkiye, the materials used in the construction of the functional system of a building which has to satisfy architectural and isolation requirements, have random and structurally unaccounted and inherent mechanical properties and high dead weight that create a burden on the engineered structural system of a building. Some of the results of seismic events in Türkiye indicate that the functional system of buildings may have a negative interference with the structural system of the buildings.

This paper provides a qualitative discussion and an analytical investigation on the negative effect of functional system on the dynamic performance of a building and suggests an initial remedy for the design codes to include such effects. Reinforced masonry construction method; a well known construction method the potential of which is unfortunately not fully realized in Türkiye; is promoted.

Keywords

Masonry, concrete frame, rigidity, ductility, seismic design

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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 total 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.

In earthquake prone parts of the world where the use of reinforced concrete with non-structural infill is a prominent construction method, the structural effect of the infill walls on the structural behavior has been investigated by many researchers. The effect of the non-structural infill is mostly investigated from a perspective that analyses its effect due to discontinuous or un-symmetric infill placement within a structure and leads to a wrong assumption that if the infill is continuously and symmetrically placed into a structure; its structural effect can be disregarded. When the non-structural infill is introduced into the load path within a structural frame, the loads that are generated within the frame are increased regardless of the irregularity of the walls. The irregularity of the walls further increases the loads due to deviations in the center of rigidity and the center of gravity of a story within a building as well as deviations in stiffness values throughout the building. Unified Building Code recognizes the important differences between the

structural behavior of a bare frame and an infilled frame and provides different design values for lateral loads. However, the Turkish Seismic Design Code 2007 does not address any difference between the behavior of a bare frame and an infilled frame.

The effect of the infills on the lateral response of a structure could be viewed in terms of its effect on the energy absorbing capacity and the vibration period of the structural frame.

Ordinary and intermediate structural frames have different ductility values and different energy absorbing capacities. These differences are reflected with the associated response modification coefficient value (R), which is a reduction coefficient for the calculated lateral load by allowing a plastic deformation to occur within the resisting frame. A higher R value indicates higher frame plasticity. In other words when an R value is used, the structure is expected to sufficiently deform to provide the required capacity to absorb and dissipate energy. However, the effect of the infill walls could prevent the infilled frame to deform, thereby preventing the frame from absorbing and dissipating the energy that it was designed for. The un-dissipated energy has to be transferred somehow and could be stored as potential energy within the structure by axial and rotational deformations of members. The outcome of this energy due to structural deformations results in increased forces and moments within the structural frame. Therefore, the structural frame, which was designed for certain force and moment values as a result of an expected structural behavior that would dissipate a certain part of the generated seismic energy, could be exposed to higher force values that are generated due to the un-dissipated energy.

Within an infilled structural frame, energy dissipation mechanisms could take place such that the infill walls could crack and be destroyed thereby dissipating an amount of energy. However, the reliability of the energy dissipation by the destruction of the infill wall would be questionable because:

1. The infill walls are seldom engineered and considered structurally to rely on its use as a structural mechanism,
2. The energy storage and dissipating capacities of different materials and structural members are different. The fact that the wall cracks, does not guarantee the dissipation of the same amount of energy as it would occur within the structural frame.
3. The infill walls may not crack at all, thereby forcing the excess energy that the structure was supposed to dissipate, to be stored within the structure as potential energy due to the deformations of the structural members and thus generating extra forces in the structural member.

Therefore if an energy dissipation value is attributed to a frame and this same energy dissipation behavior is also attributed to an infilled-frame, than the behavior and the energy dissipation characteristics of the frame must be validated.

'Figure 1' shows cracked infill walls of a reinforced concrete frame building due to the incompatible horizontal deformation behavior of the two building materials. 'Figure 2' shows structural column damage due to excessive shear forces caused by the infill walls that has extended beyond the damage that occurred within the infill walls.



Figure 1 – A typical damage pattern due to lateral loads on a non-engineered infill walls.



Figure 2 – Damaged columns as a result of increased lateral loads due to infill walls.

Although the building in Figure 1 has not collapsed, it is need of serious repair. On the other hand 'Figure 2' shows structural damage to the columns of a building beyond the damage that has occurred within the infill walls. Both these figures show that there is an undetermined effect of the infill walls on the engineered structure of a building that needs to be addressed and incorporated into the design of a structure.

On the other hand, the vibration period of the structure is directly related to the square-root of the mass and inversely related to the square-root of

stiffness of the structure. Therefore, when a structural frame is completely infilled, the rate of increase of its stiffness could be more than the rate of increase of its mass. Therefore, the period of the structure could decrease. Spectral acceleration curves indicate that as the period of a structure is lowered, the lateral loads generated by a seismic event are increased. Therefore, an increase in lateral seismic acceleration coupled with increased mass could result in higher lateral loads.

The behavior of a flexible structural frame, rigidly filled with a non-structural infill wall, could shift from that of a frame to that of a truss. The beams and the columns within this frame could be exposed to higher axial loads than they were originally designed for.

In DBYBHY 2007 which is the Turkish acronym for the Turkish Seismic Code: "The Turkish Seismic Design Code 2007"; the effects of infill walls are highlighted under the following clauses:

Article 2.3.2.3 – For buildings with B1 type vertical irregularity, if the cross-section area of the infill wall in a story is higher than the story above, they will not be included in the calculation of h_{ci} which (h_{ci} : ratio of the shear area of the structure within a story to the shear area of the structure of the story above). If $0,6 < (h_{ci})_{min} < 0,8$ than the R value of the structure will be multiplied by $1,25(h_{ci})_{min}$ and applied in both orthogonal seismic directions. The condition of $h_{ci} < 0,6$ shall never be allowed.

Clause 3.3.8 – Short columns could form due to the structural system or because of limited infill wall height along a column. If the formation of a short column cannot be avoided, the fixed end moment at the bottom of a column above a joint and the fixed end moment of the top of a column below a joint will be increased 40%. Along the total height of short column, the ties will be placed at the spacing specified only for the confinement zone for the columns other than the short columns and the vertical reinforcement will be continuous.

These two clauses that highlight the effect of infills on the lateral load acting on a structure do not provide a full treatment of the effect of the infill walls on the design and engineering of a structure. These clauses provide a local treatment of the effect of infills on the structure, and therefore there is the risk that the effect may not be considered in the global design of the structure.

Clause 2.3.2.3 addresses a reduction in the energy dissipation capacity under some circumstances and requires an increment in the seismic design loads such that, in case a B1 type irregularity exists, the R value that is used for a bare structural frame is to be reduced by $1,25(h_{ci})_{min}$. Therefore for $(h_{ci})_{min}=0,6$; R is multiplied by $1,25 \times 0,6 = 0,75$ and R remains unchanged for

$(h_{ci})_{\min}=0,8$; $1,25(h_{ci})_{\min}= 1,25 \times 0,8=1,0$. Therefore a reduction in R is addressed for walls with irregular infills. However, this clause does not address the decrease in the energy dissipation characteristics if the vertical irregularity does not exist.

Clause 3.3.8 only addresses a certain probable condition within a structure and does not address an overall strengthening procedure for the effect of infill walls.

The presence of infill walls does not necessarily indicate a certainty of structural failure. The infill walls could improve certain characteristics of the structure such as: increase the possible load-paths within the superstructure, improved story shear strength, increased compressive strength due to confinement of columns and energy dissipation due to cracking and friction within the wall elements. However, the infill walls could also adversely affect certain characteristics such as reducing the ductility of the structural frame, increased lateral loads due to increased mass and increased seismic accelerations, increased lateral loads due to increased stiffness and deviations of the center of rigidity and center of gravity of the structure and thereby generation of unaccounted off-centered forces. There are also variations in the properties of the bricks used as infill, which only increases the unknown nature of the question at hand.

Therefore, it is recommended by the authors that the engineering of a structure is incomplete without properly addressing all the possible important interactions and the effects that are expected to occur within a structure between the engineered and the non-engineered components.

The effect the infill wall on the structural behavior of a building is investigated in a simple numerical analysis for a reinforced concrete structure that consists of a concrete frame, which is later filled with bricks to form façade and interior walls. Two, 2-story 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 (presented in SI Units). 'Figure 3' shows the deflected shapes of the frames to the same scale. The mechanical properties of the materials effective on the dynamic response are for concrete: $M_c = 2.500 \text{ kg/m}^3$ and $E_c = 32.000 \text{ MPa}$ and for hollow-clay bricks: $M_b = 1.500 \text{ kg/m}^3$ and $E_b = 14.000 \text{ MPa}$. 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.

UBC-97 Spectrum, $C_a=0,4$ g

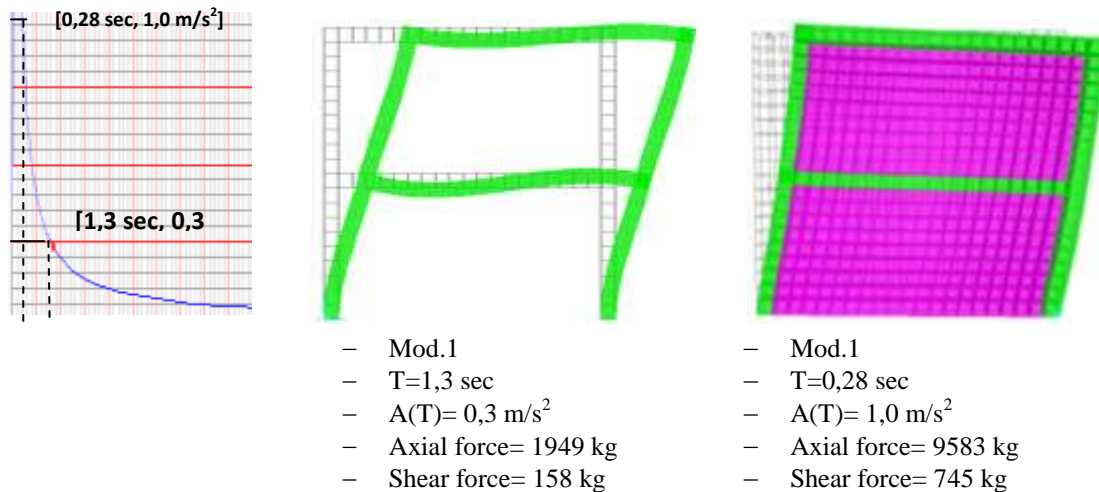


Figure 3 – Displaced shapes of a free and an infilled concrete frame under lateral action.

This model could be improved with a program that could conduct a cracked solid section and surface separation analysis. The rate of increase in the response parameters are expected to be lower than what is observed in the analysis above. However, the fact remains that the inclusion of the infill wall within a frame, increases the shear and moment values within the frame.

Another issue that needs to be addressed within the investigation of the effect of infills on the behavior of structural frames is the transfer of the loads generated within a structure due to the lateral loads. The termination points of the load paths are the foundation elements of the frames the building is composed of. Even if the infill walls and the structural frame members were able to resist the extra loads generated due to the infill walls, these loads have to be conducted to the ground through the foundation elements of the frame unless alternate paths to the ground is provided. Therefore, unless the foundation elements are modified for the increased lateral loads due to the infills, increased bearing pressures could arise underneath the foundations designed for bare structural frames.

The presence of infill walls could stiffen and strengthen a structural frame. This understanding leads to a wrong understanding that if a structure could

be stiffened and strengthened due to an infill wall, what is the problem? The problems are: 1. the structure could not be strengthened due to the infill wall, 2. the energy dissipation characteristic and thus the design lateral load for the frame is not properly determined, 3. the supposed and sometimes present strengthening effects of the walls are never quantified. Therefore a structure that is supposedly designed under a limit state design philosophy is actually left in the dark as to what the structural capacity of the designed structure actually is.

4. SUGGESTIONS FOR REVISION OF DBYBHY 2007

The codes must be simple but yet comprehensive enough to address the design parameters. Therefore, the effect of infills on the design values of lateral loads on the frames should be presented clearly. Although it would be ideal to address the issue through both parameters, the structural design with infill walls could be revised in the DBYBHY 2007 by an increased design lateral load either by addressing the lateral load increase on a structure due to decreased vibration periods or by addressing the reduced ductility. Table 2.5 of DBYBHY 2007 lists the response modification coefficients for types of structures with different ductility values. Structural systems are specified as normal ductility systems and high ductility systems and the R values are specified accordingly. The lower R value for the system with regular ductility is a result of the differences in the reinforcement use in the confinement regions of beam-column connections. However, this list does not address the change of ductility, when a structural frame designed as normal ductility or high ductility is infilled with a wall. The walls should be incorporated into the structure and designed accordingly. If the walls are not intended to be included in the structural design of a building, then they should be structurally isolated from the building. The stiffening effect of structural and non-structural infill walls for reinforced masonry construction is correctly reflected in the code with lower R values compared to ductile frames of steel and concrete. In DBYBHY 2007, for unreinforced masonry buildings is $R=2$. The code that realizes the limits of energy dissipating characteristics of masonry construction, does not consider a similar effect for infilled structural frames. Determination of these parameters will require thorough experimental and analytical research however a quick action is also required to impose a design guideline to the brick infilled structural frame construction method which is very wide spread in Türkiye. Therefore, as a least action of remedy, the lowest reduction coefficient ($1,25(h_{ci})_{min}=0,75$) that is specified in clause 2.3.2.3 which should be applied to the response spectrum coefficients should be applied to the response coefficient value of all structural frames that will be infilled. Table 2.5 of DBYBHY 2007 assigns an R value of 8 for structures

that have high ductility reinforced concrete and steel frames. The inclusion of a concrete curtain wall reduces the R value to 7 for high ductility reinforced concrete and steel frames. Therefore, as a least action of remedy, and in the absence of a thorough investigation, the response modification factor assigned for a pure frame, should be reduced at least 15% for frames infilled with non-structural bricks and masonry elements.

In UBC-97, the effect of infills on the response modification coefficients are reflected such that the R value of an intermediate moment resisting frame is reduced 25% and the R value of a special moment resisting frame is reduced 35%, when the frames are infilled.

In IBC 2003, the criteria for the satisfaction of deformation compatibility requirement among structural and non-structural components are addressed.

5. QUALITATIVE UNDERSTANDING OF MASONRY STRUCTURES

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 is justified as a result of the fact that non-structural functional components of a building could have negative structural effects. 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 wall components of the building within its structural system. Therefore, all the structural boundary elements as well as the infill wall elements within the structure is engineered and structurally designed. 'Figure 4' 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.

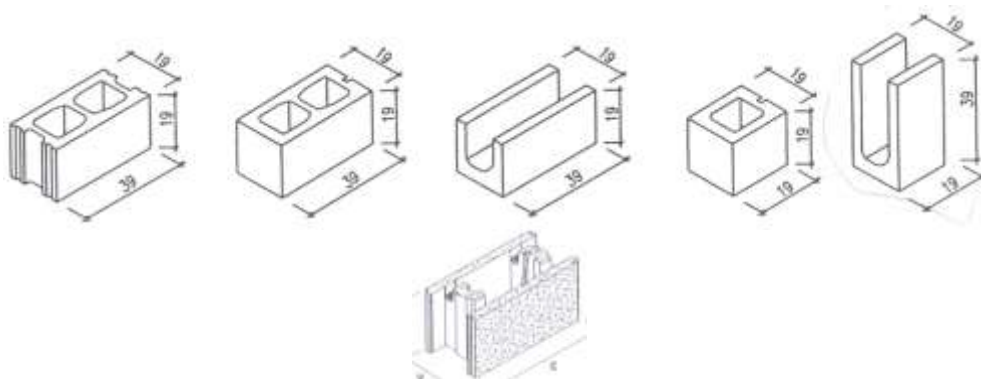


Figure 4 – Typical examples of masonry units.

Masonry provides compressive resistance, stability, weathering durability, energy efficiency, and fire protection to the building and it can be used for

load bearing 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, 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.

6. STRUCTURAL ASPECTS OF MASONRY CONSTRUCTION

The hollow masonry units can be laid in many patterns, as shown in figure 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. 7’ could also be viewed as a structure where the beams and columns are hidden within the walls.

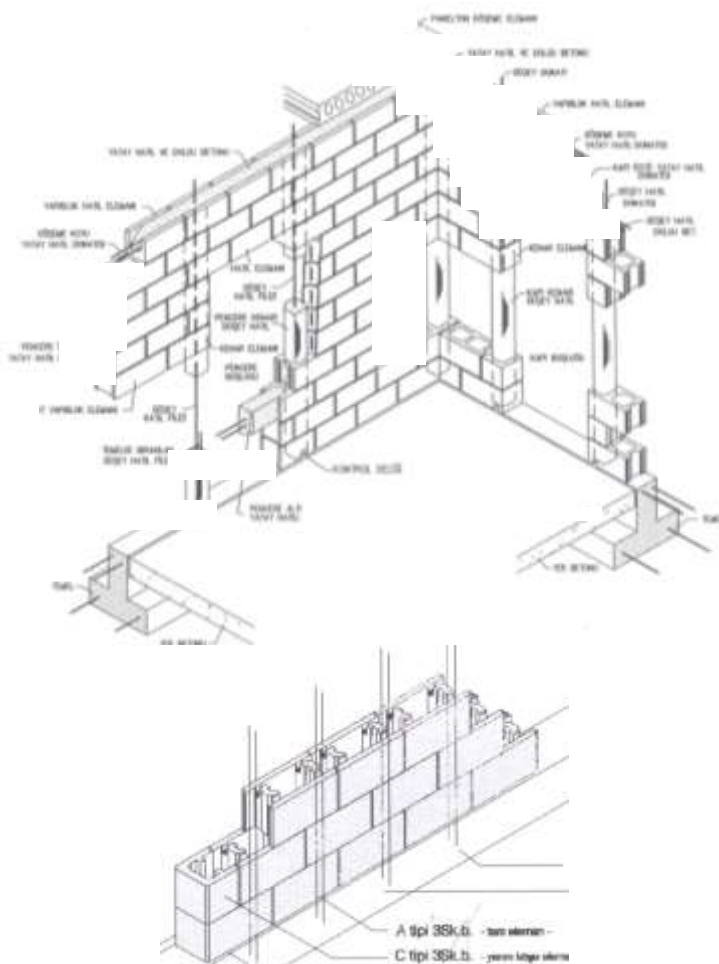


Figure 7 – Structural elements within precast masonry construction.

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 8' shows the formation of such piers within the walls that are formed from unique masonry units.

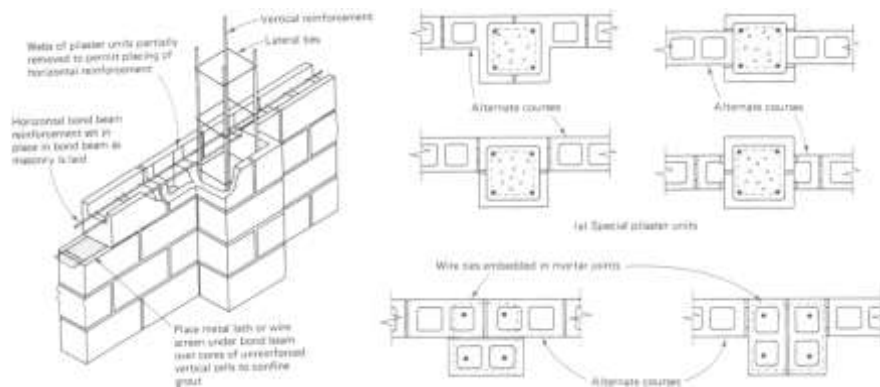


Figure 8 – Use of masonry units to construct piers.

7. A MODERN APPLICATION OF MASONRY CONSTRUCTION

The following project is comprised of 3-story houses with a basement and two stories above the ground level. The structures are built with the reinforced masonry and hollow core slab system which includes precast hollow core slabs as rigid diaphragms supported by reinforced masonry units as vertical and lateral load bearing wall elements. The structures were designed based on the ACI guidelines since the DBYBHY 2007 does not cover the design of reinforced masonry structures.



Figure 11 – Arkeon Evleri.

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

- Slabs: 0,236 t/m²
- Slab topping (7cm): 0,168 t/m²
- Flooring: 0,1 t/m²
- Architectural wall load: 0,050 t/m²
- Live load: 0,2 t/m²
- Balcony and staircase live load: 0,350 t/m²
- Snow load: 0,075 t/m²

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 story 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, DBYBHY 2007 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]

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

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

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

$$F_b = 0.33f'_m$$

- 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:

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

Note that the design axial and design bending capacities of the masonry elements are determined with allowable stresses based on low material constants. The slenderness of the walls is taken into account for the calculation of their allowable compressive capacities. The building was designed for R=2.5 which is suggested by ACI for reinforced masonry structures.

Had this structure been a reinforced concrete frame, according to DBYBHY 2007, it could have been designed for a lateral load obtained by R=8. Therefore, this reinforced masonry structure is designed for a lateral load that is %320 higher than the lateral load that would have been used to design a reinforced concrete structure.

6. CONCLUSION

A building is composed of many characters, some of which is designated to be structural and some to be functional. Some of the formations within a building that are thought to be independent of the expected structural behavior of a building could in fact have an effect on the response and reaction characteristics of the building.

A design process involves an understanding. Current civil engineering design and code philosophies strive to understand and determine the behavior of a structure up to its ultimate strength limits. Previous design methodologies were criticized for its lack of investigation depth of material characteristics, structural member behavior and overall design limitations. Modern civil engineering practices do not solely rely on conservative assumptions and experience based on historic field experiences and strives to implement a scientific method of design based on rationality and statistics. Therefore, current design practices for structural frames must be improved to incorporate the effect of non-structural infill walls.

DBYBHY 2007 must be improved to address the effect of masonry infills on the behavior of structural frames and must include the reinforced masonry design guidelines as a powerful method that extends structural design to a greater domain within a building.

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