PREDICTION OF REINFORCED MASONRY WALL BEHAVIOR BY SIMPLE MODEL ANALYSIS AND FINITE ELEMENT ANALYSIS

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ABSTRACT

Reinforced masonry wall specimens were experimentally tested under the context of TAISHIN project in El Salvador in 2005. The specimens were built using concrete block units, which is one of the most common masonry types used for dwelling in the country. A total of 4 specimens will be analyzed in this study with two main variables: ratio of horizontal reinforcement and lateral load pattern. In case of the former case, a horizontal bar spacing of 400 mm and 600 mm is given according to the provisions given in both codes: the actual code of 1997 and the new code draft of 2004, respectively. In case of the latter, monotonic and cyclic load pattern is given. Failure of all specimens resulted to be due to flexural behavior in the wall. A prediction of the observed experimental behavior of wall specimens is intended to be simulated using two different methods: a simple model analysis proposed by Miha Tomaževič and a discrete cracking model in finite element method. The suitability of the prediction of both methods is checked by the comparison of several characteristics of the behavior of masonry walls under lateral loads observed in the experimental program. Both methods show good prediction for flexural behavior. However, fitting of some parameters in both methods should be carried out to represent other possible failure modes expected in masonry walls.

Keywords: Reinforced masonry, interface elements, flexural behavior.

1. INTRODUCTION

From the observation of damages and death toll caused by most recent seismic events in El Salvador, it can easily be said that masonry structures represent the structural system with highest vulnerability along the national territory. Also, masonry structures represent the highest percentage of use in single and two-floor dwellings in both rural and urban areas. As a response, the national government through the Ministry of Public Works and some other institutions has proposed in 2004, a new design code for masonry structures but, it is not officially authorized yet and intended to substitute the actual code of 1997. Some other efforts have been done with the assist of the Japan International Cooperation Agency (JICA) and other national institutions involved in the develop of an experimental program with the objective of achieve a better comprehension of masonry structures commonly used in El Salvador leading to the development of TAISHIN project in 2005 and with the main objective of improve the design and construction practices suggested in the codes in case of masonry. Many different masonry types were tested, however only concrete block masonry is analyzed due to the high use in the construction of dwellings in the country.

A total of four specimens are analyzed in this study. The experimental results from the specimens are studied under the point of view of their resistant mechanism and failure mode when subjected to the lateral loads including: initial lateral stiffness, behavior of steel reinforcing bars, maximum strength of the wall and degradation of the stiffness and strength. Also, special attention is

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paid to the cracking patterns developed in each important stage of the behavior of the wall. Displacement transducers, strain gauges and pictures record are available from the experimental program and are used in the description of the resistant mechanism of each specimen.

As a main objective of this study is the prediction of the behavior of the specimens analyzed in the experimental program. This is done by the use of two methods: a simple analytical model and finite element method. The selected analytical model is the well-known proposal by Miha Tomaževič in 2000. This model includes three types of failure modes: sliding, flexural and shear failure in the wall panel. Several formulations in order to evaluate each failure mode are given by the author and used for the prediction of the behavior of the wall. In case of finite element method, a discrete cracking model is chosen for the definition of the models due to the cracking pattern observed in the experimental program which in case of diagonal cracking, runs through the vertical and horizontal mortar joints, and in some cases pass through the brick units. The discrete crack model is then defined by the use of plane-stress continuum elements and line interface elements in order to represent the masonry units and the potential cracking paths in the mortar joints and bricks, respectively. Constitutive laws of materials are given to these elements in order to simulate the expected behavior within the wall.

2. OBSERVED EXPERIMENTAL RESULTS

2.1. Description of masonry wall specimens

Geometrical characteristics were kept constant in all four specimens. Concrete block units with nominal dimensions of 100x200x400 mm were used in 14 layers from bottom to the top of the wall. The total length of the masonry wall panel was 3000 mm and the height was 2800 mm. The vertical reinforcement consisted of 5 deformed steel bars spaced at 600 mm with a diameter of 9.5 mm. One extra vertical bar (Ø 9.5 mm) was included near the extreme sides of the wall with a spacing of 200 mm as suggested in 1997 and 2004 codes making a total of 7 vertical bars. Horizontal reinforcement was placed within the mortar joint and consisted of deformed steel bars spaced at 400 mm or 600 mm (provisions of 1997 code and 2004 code, respectively) of 6.35 mm of diameter in both cases. Reinforced concrete foundation beam with dimensions 300x200x3800 mm (width x height x length) was provided, with longitudinal reinforcement of 6 bars Ø9.5 mm and stirrups space at 200 mm with bars of Ø6.35 mm of diameter. A top beam was also included at the top end of the masonry wall panel, made of reinforced concrete, with dimensions of 150x200x3000 mm and 4 longitudinal reinforcement bars of Ø9.5 mm of diameter and stirrups spaced at 200 mm with a diameter of Ø6.35 mm. Monotonic and cyclic load was applied at the top portion of the top beam. Further description regarding the experimental program is given in the report developed in TAISHIN project: “Results of investigation of reinforce concrete block construction system” (2008). The set-up of specimens experimentally tested for in-plane loading is shown in Figure 1.

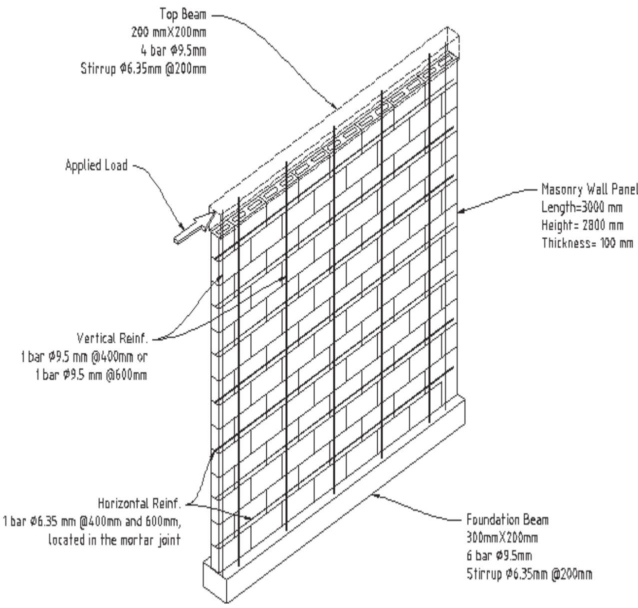

Figure 1. Experimental set-up of all specimens.

2.2. Observed experimental behavior

The behavior observed during the tests of each specimen will be the main characteristic to be compared with the prediction of the models mentioned above. It can be said that all specimens showed a common behavior when subjected to monotonic and cyclic load. The main failure mode observed was flexural failure. This was concluded after analysis of damage process, load and displacement curves and cracking pattern in the wall along the test. The observed resistant mechanism was as follows: First horizontal cracks appeared in the mortar joints at early stages of loading due to the tension stresses developed due to the bending moment induced to the wall. Due to the opening of these cracks, vertical reinforcement with the compression of masonry units is the mechanism holding the wall. After some load increments, yielding of vertical reinforcement was observed. Visible diagonal cracks were found in the wall following the compressive strut of the panel. Due to the increase of tension stress, the crack opening leaded to a significant reduction of lateral stiffness of the specimen. This point is treated as the first cracking point even though several cracks have already appeared in the wall. Appropriate amount of horizontal reinforcement withstand the tension stresses developed in this cracks and the wall was able to resists more load increments. Yielding of horizontal reinforcement was observed and all the resistance of the wall panel is re-located in the compression strut of the wall in the most compressed side. At this point, considerable damage is already seen in the wall. The achievement of the maximum strength corresponded to achievement of the maximum deformation of masonry units in the compression zone, when crushing of units was observed. Finally, the wall was subjected to more displacement until reaching the ultimate state, when heavy damage was observed in the wall. Load and displacement curves were obtained for all specimens and are shown on Figure 2 and Figure 3 according to the design provision used in the wall (1997 code or 2004 code). Characteristic cracking pattern is also studied using the pictures record and is defined by the formation of horizontal cracks running through the mortar joints in the tension side of the wall, diagonal cracking running through the mortar joints and some brick units and finally, crushing of the masonry units in the compression side of the wall.

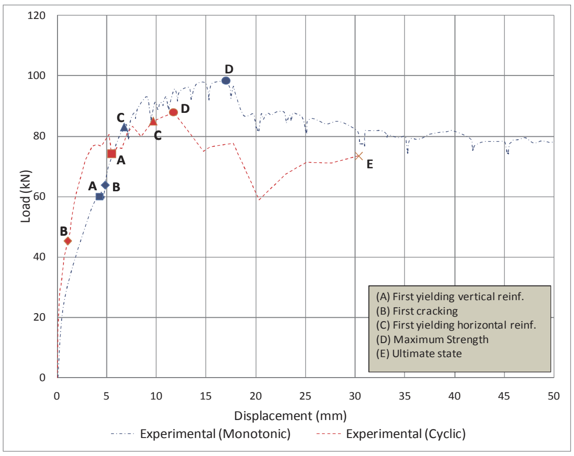

Figure 2. Load-displacement curves for specimens designed under 1997 code provisions.

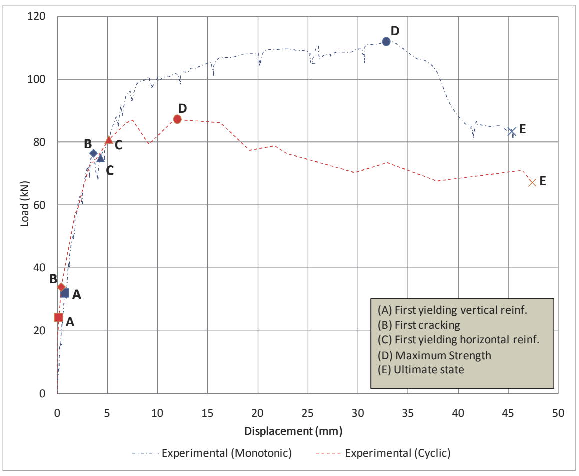

Figure 3. Load-displacement curves for specimens designed under 2004 code provisions.

Suitability of design provisions are not discussed in this study, but as can be seen, no significant contribution is giving for different horizontal reinforcement ratios. This could not be accounted due to the induced flexural failure in all specimens.

3. PREDICTED WALL BEHAVIOR BY SIMPLE ANALYTICAL MODEL

3.1. Description of analytical model

The simple analytical model chosen for this study is proposed by Miha Tomaževič in 2000. This model is considered due to its well-known acceptance worldwide, its experimental basis supporting the formulations and the failure modes considered in the wall behavior. The three failure modes considered in this model are divided in: sliding, shear and flexural failure. The calculation of the strength for each failure mode is given by the following assumptions:

- Sliding strength: In case of reinforced masonry, it is assumed that the resistance is given only by the dowel effect of the vertical reinforcement located in the horizontal cracks along the sliding plane (dowel action as defined by M.J.N. Priestley and D.O. Bridgeman, 1974).
- Flexural strength: It is calculated as equilibrium in the section analysis of the wall, assuming that the yielding of the vertical reinforcement located in the tensioned side of the wall happens simultaneously with the crushing of the masonry units located in the compression side, as given in EC6.
- Shear strength: It is based on the contribution of arch-beam mechanism and truss mechanism proposed by M. Wakabayashi and T. Nakamura, 1998. The combination of arch-beam assumes that compression is carried by an arch formed by the vertical reinforcement and masonry. Truss mechanism assumes that tension is carried out by the remaining part of vertical and horizontal steel and masonry (Tomaževič, 2000).

Specific equations are given for each calculation of strength and some parameters are suggested by the author. The suitability of these equations is checked plotting the levels of the calculated strength in the load-displacement curve in order to define the calculated failure process of each specimen.

3.2. Results of calculation by simple analytical model

In Figure 4 and Figure 5 it is plotted each calculated strength against the load-displacement curves of specimens designed under 1997 code and 2004 code provisions, respectively. As can be observed in both figures, flexural strength is well predicted in all cases, more accurately in case of cyclic loading cases. This is due to the fact that code provisions aim to induce flexural failure on the wall by the use of horizontal reinforcement, as observed in the experimental program. However, it is expected at first the sliding failure of the specimens but this did not happen in the experimental program. It can be said that sliding strength is underestimated and some other mechanisms such as friction in the mortar joint, increment of the friction coefficient due to compressive stress in the compressed side of the wall and interlocking is not taken into account in the formulation. It is discussed in here that the contribution of the dowel action of vertical reinforcement is given just after the formation of the cracks in the joints and may not be taken as the only resistant mechanism accounted for sliding behavior.

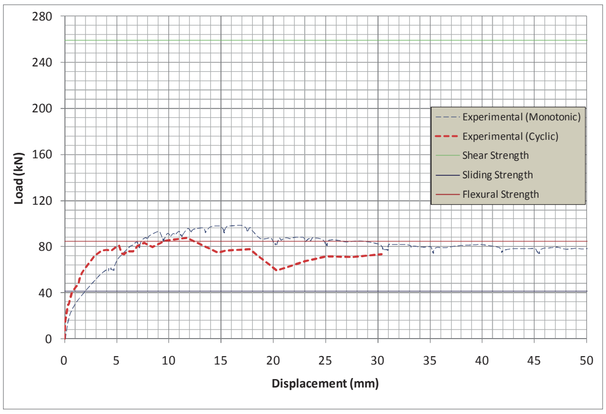

Figure 4. Calculated strengths for specimens designed under 1997 code provisions.

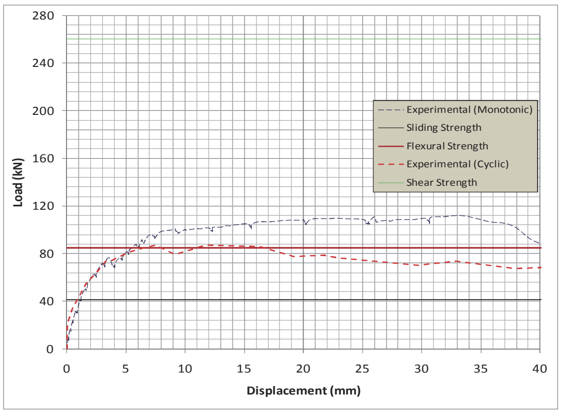

Figure 5. Calculated strengths for specimens designed under 2004 code provisions.

Shear strength is considered as overestimated in the calculation. This is attributed at the suggested tribute area considered in the arch-beam mechanism of 50% of the total width of the wall. This percentage is considered as excessive and it is proved with the finite element results. However, it is necessary to evaluate experimentally the actual value of shear strength of the specimens. Future tests with similar specimens but with induced shear behavior are needed to accurately asses the validity of the formulation by Tomaževič.

4. PREDICTED WALL BEHAVIOR USING FINITE ELEMENT METHOD

4.1. Description of the discrete model

A discrete cracking model is chosen for this study due to its advantages against smeared crack model in terms of the cracking paths expected in the wall. From observation of the experimental results, it is easily seen that most of the cracks occurred in the bed and head joints of the wall. Because of this, the discrete model proposed in this study consists in the combination of 8-noded plane stress continuum elements (QU8), 4-noded line interface elements (IL22) and truss elements (BE2). The software tool is DIANA v. 9.3. Plane stress elements are used for the simulation of masonry units and concrete elements (top and foundation beams) and are given with the compressive behavior intended to reproduce crushing of these elements using a Von-Mises ideal plasticity model. Interface elements represent the mortar joints (head and bed joints) which are given with frictional behavior to reproduce sliding with the use of a Mohr-Coulomb friction model. Also, a potential vertical crack running through the masonry units is given at every half brick and simulated with interface elements. The behavior given to these cracks is representing tensional behavior by the use of a linear tension-softening model. Finally, truss elements are representing the vertical and horizontal reinforcing bars under tensional behavior and described by a Von-Mises ideal plasticity model. The constitutive laws parameters were obtained from the available test results in the experimental program, and, some other are obtained from past researches (Cabrera, 2003 and Lourenço and Rots, 1997).

The simulation is only done in case of monotonic loading specimens. Lateral load is controlled by displacement increments with a step size of 0.05 mm until reaching 20 mm of total horizontal displacement at the top of the wall (1/150). Regular Newton-Raphson method with force tolerance of 10 kN is given for the iterative procedure. Vertical load simulating the self-weight of the panel was distributed in 3 points along the top beam. High capacity of deformation is given to constitutive laws in order to keep the stability of the calculation. Finally, perfect bonding is considered for the reinforcing bars.

4.2. Results of prediction by finite element analysis

Load-displacement curves are obtained as a result of calculation and plotted against the experimental one. Figure 6 and Figure 7 shown the results for the 1997 code and 2004 code specimens, respectively. It can be seen in this Figures that the behavior of the wall can be well-predicted by this method. Higher strength values were obtained and may be attributed to the use of perfect bonding in the reinforcement. Lateral stiffness, yielding of bars and crushing of the units is well predicted in the process of failure of the wall. Cracking pattern at each step is also calculated and a good agreement can be observed. Particular cracking such as horizontal cracks in bed joints, diagonal cracking in bed and head joints and crushing of units is well predicted. Maximum crack width calculated is 4 mm and is in compliance with the observed in the experiments. Behavior and yielding of vertical and horizontal reinforcement can be also calculated and roughly well predicted. In case of vertical reinforcement, the calculation of reinforcement is accurately done. Finally, it can be checked the formation of the arch-beam mechanism of the wall. However, at maximum strength point (corresponding to the crushing of the units), a compressed total length of 20% of the length of the wall is found to be under high compressive stresses. This can be used to calibrate the 50% suggested by Tomaževič and that is supposed to lead to overestimation of shear strength of the wall.

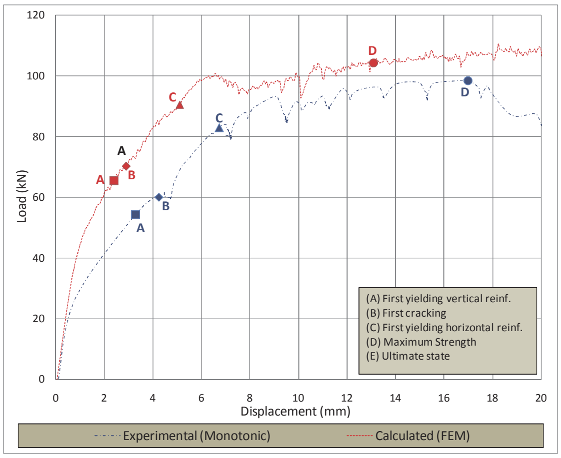

Figure 6. Load-displacement curve obtained for specimen designed under 1997 code.

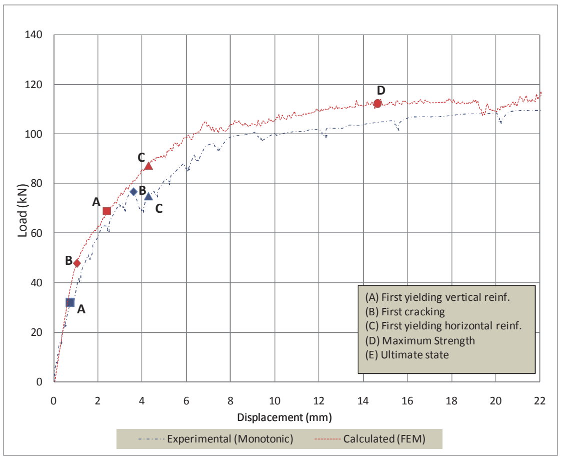

Figure 7. Load-displacement curve obtained for specimen designed under 2004 code.

5. CONCLUSIONS

The applicability of two methods of analysis of reinforced masonry walls is checked. It is seen that both gives accurate results in case of masonry walls governed by flexural behavior. However, in case of simple model analysis, some parameters should be fit prior to its use in practical applications. Some experimental studies should be carried out in order to establish the actual sliding and shear strength of the masonry walls due to the fact that it is not well captured by the equations proposed by the author in the cases studied in here. In the other hand, finite element method is able to capture the process of failure and strength of the specimens. It is suggested to carry out some experimental tests in order to validate the parameters chosen for the frictional behavior of the mortar joints, which are obtained from past researches. Also, it has to be experimentally tested the bond-slip behavior of reinforcing bars.

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