Seismic Pushover Analysis of Existing Masonry Structures

Abdulhamid Zahir[1*], Stefania Rizzo [2+], Erkan Çelebi [1], Lothar Stempniewski [2]

[1]Institute of Natural Science, Sakarya University, Sakarya, Turkey
[2]Institute of Reinforced Concrete Structures and Building Materials, KIT, Karlsruhe, Germany
[*]Corresponding author: abdulhamid.zahir@ogr.sakarya.edu.tr
[+]Speaker: abdulhamid.zahir@ogr.sakarya.edu.tr
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Abstract
Masonry structures are more vulnerable than another structure types during earthquake. These type of structures represent a large percentage of the built environment in Turkey, generally used as residential purpose. A lot of heritage buildings are seen there as well. The last century's earthquakes, including 1999 Düzce and Izmit disasters, have shown how masonry structure can fail catastrophically and caused to a lot of dead and economic lose. With keeping this on mind, the structures in those areas should be assessed seismically and discussed if they are safe or not. The aim of this paper is to model and analyze the nonlinear behavior of confined masonry structures under lateral loads numerically and evaluate the performance of them. Nonlinear static pushover analysis which is an effective and suitable strategy for analysis of seismic in-plane response of walls and buildings, through 3D equivalent frame modeling is applied. This modeling technic has been implemented in Tremuri package program. In this paper a confined masonry structure is considered as a case study, which is located in Sakarya province and built in the second half of the 20th-century. The behavior of RC beam elements is idealized as elastic-perfectly plastic with limited resistance and plasticity concentrated at the end-element. To assess seismic behavior of masonry structures, the failure mechanisms of masonry walls under influence of in-plane loads are obtained. Then the damage pattern of walls and the lateral load-displacement curves are determined. The performance level of building is discussed. According to the results obtained, some part of walls are failed in shear and some part of them affected by flexural.
Keywords: Confined masonry structures, Macro-element modeling, Nonlinear pushover analysis, lateral loads, Performance level.

1. Introduction
Masonry construction is widely preferred because of its low cost, widespread geographical availability, thermal insulation, protection from fire, durability, low maintenance cost and it is easy to construct. This type of structures behave well against vertical loads since they have good compressive strength but they are exposed to failures against horizontal loads. There are not much technological development and research is done in this area. Due to these reasons, masonry structures are constructed without technical support and may be significant errors are made during construction. Therefore, they are more vulnerable against natural disasters such as earthquake and are severely damaged or even destroyed. During the 1999 Gölcük and Düzce

disasters which have shown catastrophic failures and resulted to a lot of dead and economic loss (Efe, 2000). According to observed buildings in the last decade's earthquake the masonry structures are exposed to more serious damages than did RC buildings. With this in mind, the existing structures need to be seismically assessed and in case of necessity should be rehabilitated to reduce the overall risk to life-safety and property loss.

In recent years nonlinear analysis methodologies are being used for retrofitting existing building and designing new ones due to use of optimized structures, use of new materials and addressing safety related issues of structure more rigorously. Nonlinear static pushover analysis which is a suitable method to estimate the seismic in-plane response of walls and buildings due to its simplicity and efficiency (Jiang et al., 2010), is frequently used based on macro modeling in masonry structures. Pushover analysis, in terms of initial stiffness, base shear strength and displacement capacity, is commonly used in order to determine the capacity curve of walls. In academic research field two modeling methods as macro and micro strategies are employed to model the behavior of masonry structures (Lourenço, 2002). The concept of using structural component models designated by macro-element modeling for masonry structures was introduced in the 1970s by Tomaževič (1978) and applied to perform seismic assessment. The macro element in Tremuri considered is taking into account overturning, damage and frictional sliding mechanisms is proposed by authors (Gambarotta & Lagomarsino 1997., Brencich & Lagomarsino 1997).

Confined masonry walls consist of panels and tie elements. The panels (piers & spandrels) are presented as macro-elements reproducing some collapse (Braga & Liberatore 1991), connected by rigid areas, and while the RC columns and beams are considered as elasto-plastic elements with stiffness and ultimate strength related to the constituent material and geometric configuration (Magenes & Calvi, 1996). According to Tomaževič (1997) the behavior of confined masonry is more ductile. Shear cracks occur with distributed diagonal cracks then cracks pass to tie element like columns. Finally columns buckle and collapse occur. The failure mechanism of masonry structures may be complicated, is affected by the interaction of horizontal, vertical components and by axial loads. Spandrel is exposed to early shear cracking but the ultimate resistance is given by pier failures. The shear cracking strength is dependent on the degree of flexural moment. The first diagonal crack is produced by shear force due to tension, effected by bending moment on the top of wall. This study model and analyze the nonlinear behavior of a confined masonry structure under seismic loads numerically and evaluate the performance of it.

2. Masonry Structures

The oldest type of structures which are built from individual units laid and bound together by mortar. Bricks, tiles, granite, limestone, glass block, concrete block, marble etc. are the masonry units used in construction of it. Even though there are a lot of researches and studies done in literature, the global behavior of masonry buildings under lateral loading is not well understood. The failure modes depend on the construction type, the size and amount of opening and the connection of vertical elements to the diaphragms. The principle in-plane failure mechanisms of unreinforced masonry (URM) walls subjected to earthquake actions can be summarized as shown in Figure 1. Confined masonry (CM) structures consists of unreinforced masonry walls confined with vertical and horizontal concrete bands around openings and masonry panel which resist against vertical and horizontal loads. These concrete bands are referring to tie column and tie beam. In contrast to concrete frame, the walls are load bearing and after construction of them columns on four side will build to resist out of plane bending of walls.

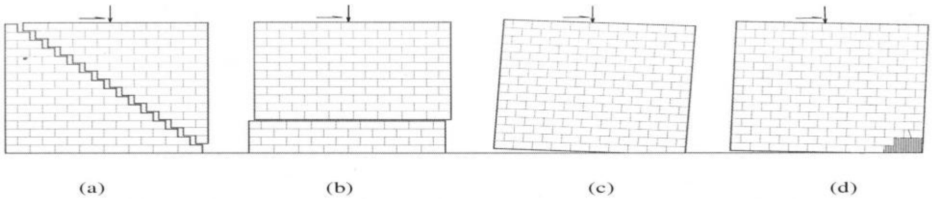


Figure 1. Typical failure modes of a URM wall. a) Diagonal tension b) Bed-joint sliding c) Rocking d) Toe crushing (ElGawady 2007)

3. Structural Modelling Approaches for Masonry

3.1. Macro-Element Modelling of Masonry Structures

The macroelement model assembled of piers and spandrel beams to form equivalent frame. It is two-dimensional model capable to simulate the in-plane behavior of masonry panels. The two-node macroelement can represent the axial and flexural response and interaction of shear and flexural damage. The macro-element model described in Tremuri is the one developed by Gambarotta and Lagomarsino (1996), consist of three layers: bending and axial effects concentrated in parts 1 and 3, while shear deformation influences part 2 as Figure 2 (a and b).

3.2. Equivalent Frame Modeling of Masonry Structures (EFM)

Equivalent frame modelling approach is a simple and effective approach to carry out nonlinear analysis of masonry structures. In this method, the walls are considered as an idealized frame, in which deformable elements (piers and spandrels) connect rigid nodes as Figure 2c. These elements are the parts of wall where the nonlinear response is concentrated. However, rigid nodes are not subjected to damage. Piers are the main vertical element carrying both vertical and lateral loads while the spandrels are called secondary horizontal element to couple the response of adjacent piers in the case of lateral loads. The spandrels by allowing or carrying end rotations affect the boundary condition of piers. Thus they have significant influence on the wall lateral capacity. The global model defined by assembling the in-plane contribution of the masonry walls and floors. The in-plane behavior of masonry walls with openings may be discretized by a set of masonry panels where expose to cracks and failure modes (Magenes et al., 1998; Galasco et al., 2004). The out of plane effects in walls with respect to the overall behavior of the structure are neglected. The implementation of equivalent frame model is presented in Tremuri program. Tremuri program originally developed at university of Genoa (Galasco et al., 2004; Lagomarsino et al., 2012), thereafter the commercial version of it as 3muri (S.T.A.DATA s.r.l., release 11.5.0.8) developed. Masonry panels (piers and spandrels) are modeled as 2D elements bi-linearly with strength degradation and stiffness decay in nonlinear phase; nonlinear RC elements (columns and beams), modelled as 2D and 3D respectively, are idealized according to assumption by which elastic-perfectly plastic hinges concentrated at the ends of element (Cattari and Lagomarsino, 2012).

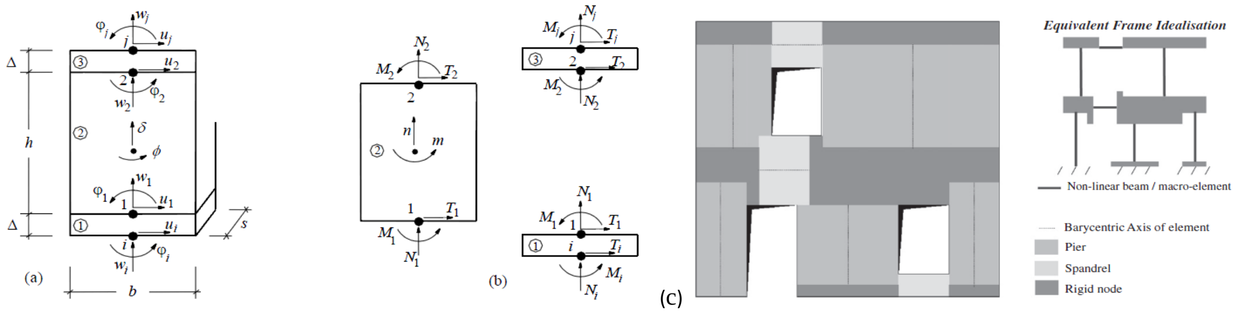


Figure. 2. a) , b) Kinematic model for the macro-element (Gambarotta and Lagomarsino, 1996) and c) equivalent frame model idealization (Lagomarsino and Cattari, 2009)

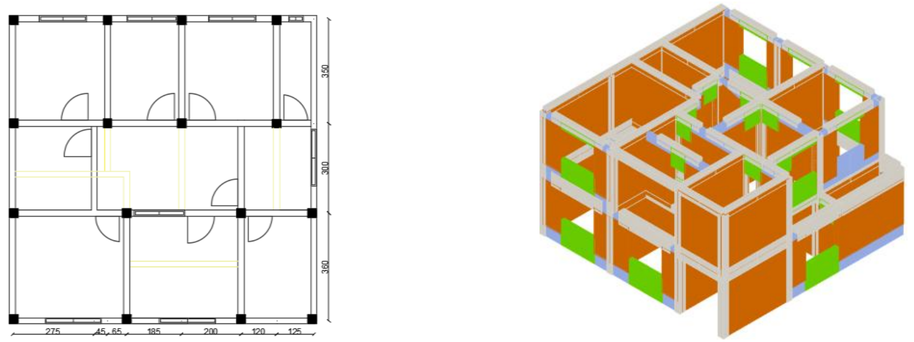
4. Seismic Analysis Procedures and Results

Nonlinear seismic analysis is a broad type of methods which use nonlinear behavior to determine the overall inelastic response of structures. In order to apply nonlinear seismic analysis of masonry buildings, incremental static (Newton-Raphson) procedure with displacement control has been implemented. In this procedure, the building is subjected to an increasing static load pattern. A nonlinear beam element model has been implemented in 3Muri for modeling masonry piers and spandrels (Figure 4). A confined masonry building of about 10mx10m which is located in Sakarya and built in 1984 selected as the case study (Figure 3), set out of two levels, ground floor and first floor. The walls are made up of vertical perforated brick blocks with cement reinforced lime mortar. All walls have 20cm thickness. Floor structures are made up of concrete slabs. The slabs are considered flat concrete with 12cm thickness. Material properties are reported in Table 1.

Table 1. Material properties adopted for the case study

	f_m N/cm^2	τ_0 N/cm^2	E N/mm^2	G N/mm^2	W kN/m^3
Masonry Walls	620	14,29	3255	1302	12
RC Elements	24(N/mm2)	-	28000	11200	25

As seen in pushover curves, the building has higher strength in the Y direction than the X direction. Existing of more openings on the side walls can be the one reasons for better behavior of building in Y direction.



a) b)

Figure 3. a) First floor plan view and b) geometric model (3Muri)

Results of pushover analysis performed on the whole building along the x and y directions under different load patterns in term of pushover curves are illustrated in Figure 5.

The target (d_t) and ultimate (d_u) displacements of the structure are compared for safety verification. The target displacement must be lower than the ultimate one, which is assumed to be correspondent to 80% of the maximum base shear. The seismic demand was defined for Sakarya with 475 years return period and 5% critical damping ratio.

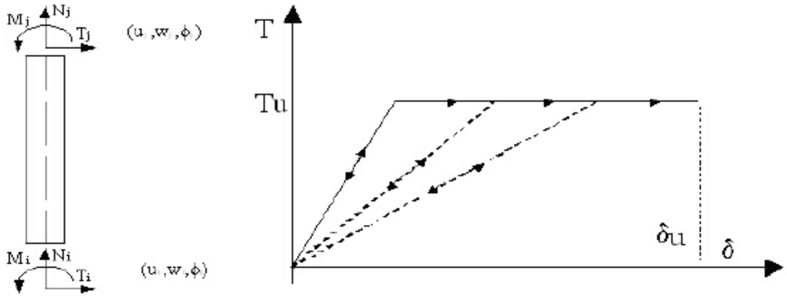
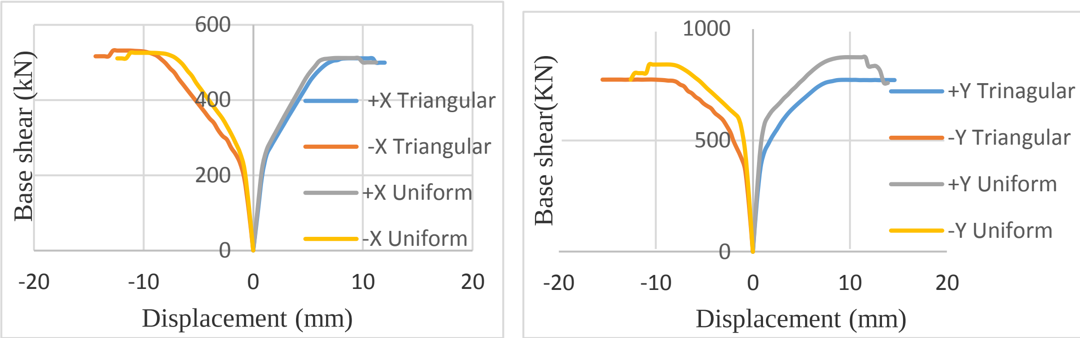


Figure 4. Non-linear beam degrading behavior (3Muri manual)



a) b)

Figure 5. Pushover curves a) in X direction and b) in Y direction

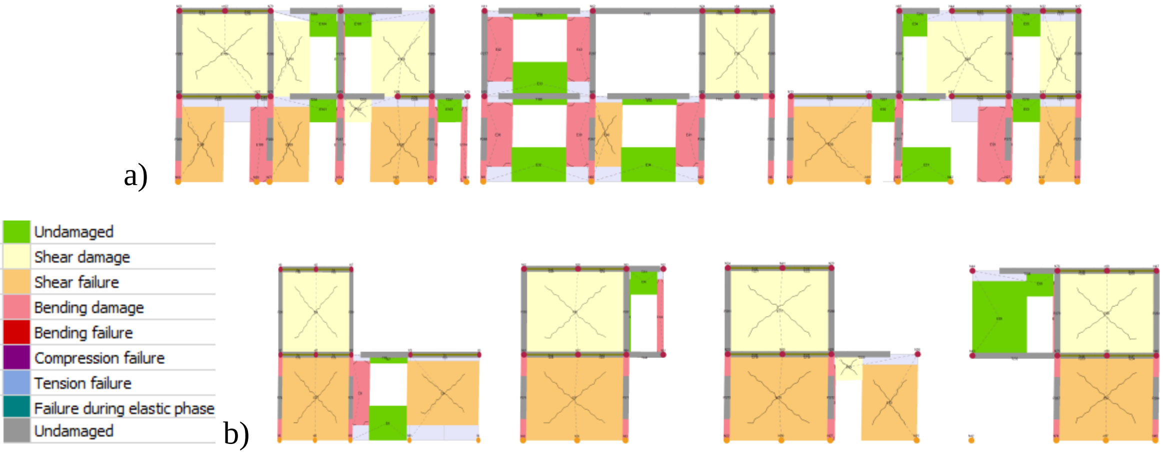


Figure 6. Damage patterns from 3Muri corresponding to the (a) X and (b) Y directions

Table 2. Target and ultimate dispacements from 3Muri

	d_u (m)	d_t (m)
+X Triangular	0,009	0,1208
-X Triangular	0,0108	0,1398
+X Uniform	0,0084	0,1095
-X Uniform	0,0093	0,1181
+Y Triangular	0,0109	0,0490
-Y Triangular	0,0116	0,0521
+Y Uniform	0,0105	0,0269
-Y Uniform	0,0094	0,0238

As shown in Table 2, the target displacements are higher than the ultimate displacements for both load patterns and directions. For instance, the ultimate displacement in +X direction is just 8% of the target displacement. Therefore the building's performance level is determined as collapse and the necessity for strengthening is inevitable. This building was previously analyzed linearly with StatiCAD (2013) program as well. According to the StatiCAD analysis the performance level of building was determined as same as the current analysis, but the failure in the walls is based only on the shear effect. However, in the nonlinear analysis, walls are affected from both shear and flexural. In static linear analysis, the response of building is considered in the linear elastic range and the model's stiffness matrix is constant. On the other hand, the nonlinear analysis methods deal with the post-elastic behavior of structures.

5. Conclusions

In this paper, the seismic assessment of an existing confined masonry building through nonlinear static procedures is discussed. Equivalent frame modeling approach considering Tremuri program (lagomarsino et al., 2012), is used. According to some assumption in Tremuri the out of plan failure of walls is neglected. The focus herein is only on the in-plane behavior of structures. In conclusion, from results it may be stated that so-called building does not verify the possibility of no-collapse situation and the necessity for strengthening is needed. As seen in damage patterns, the first floor columns are affected from bending and the panels are failed in shear failure as well as flexural damage. As mentioned above the case study was analyzed linearly in StatiCAD program before. In the results, there was occurred only shear failure while in current study the flexural damage occurs as well as shear failure. That is why the nonlinear analysis has recently preferred for analyzing of structures.

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