Pushover Analysis for Seismic Evaluation of Masonry Wall

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***Abstract*—The present work investigates the seismic evaluation of unreinforced masonry (URM) walls when subjected to seismic (lateral) loading. The work consists of modeling the geometry and property of masonry wall. After which non-linear analysis was performed using SAP 2000 software. The paper is divided in to two parts. One part reveals the size of finite element meshing suitable for modeling a unreinforced masonry wall in SAP 2000 software. While the other part investigates the result of nonlinear static analysis performed on selected model.**

***Index Terms*—seismic evaluation, unreinforced masonry wall, SAP 2000, finite element meshing, non-linear static analysis**

I. Introduction

A. Importance of Work

Masonry structures are most common types of structures used since ages. Now-a-days such type of constructions is commonly employed in rural regions, since it is economical and accommodates itself according to prevailing environmental conditions. It has been observed that under the action of moderate to severe earthquake occurrences (e.g. Bihar 1988 [1], Garhwal 1991 [2], Killari 1993 [3], Jabalpur 1997 [4], Chamoli 1999 [5], Bhuj 2001 [6], Sumatra 2004 [7], Jammu and Kashmir 2005 [8], Sikkim 2006 and 2011 [9], [10], Nepal 2015 [11]), the masonry buildings performed the worst, causing the largest loss of lives as well as the properties of the residents. Thus in order to save the life of people from collapse of such buildings during earthquake it is required to make them earthquake resistant. For existing buildings seismic retrofitting is needed. The first step before actual retrofitting is adopted as a strategy will be an assessment of the seismic resistance of the existing buildings. Nonlinear analyses of unreinforced masonry (URM) buildings and wall components have been conducted in different parts of the world in order to investigate rehabilitation requirements of such buildings. The main objectives of the paper are (i) To validate the proposed model of masonry wall in SAP2000 software and (ii) To perform pushover analysis on the validated masonry wall in order to assess its performance. The work done by different authors is illustrated in literature review.

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B. Literature Review

The literature work can be discussed in following manner:

1) Modeling of masonry wall

Modeling of masonry wall is the first step in analytical analysis. The outcome of analysis is completely dependent on the accuracy of modeling. Lourenco [12] presented the two models for micro and macro analysis of masonry structures. Gambarotta and lagomarsino [13] proposed the damage model for mortar joints applied to an extended approach for the evaluation of the lateral response of in-plane loaded brick masonry shear walls. Sivaselvan and Reinhorn [14] presented the development of a versatile smooth hysteretic model based on internal variables, with stiffness and strength deterioration and with pinching characteristics. Azevedo *et al*., [15] analyzed the seismic behavior of structures composed of masonry blocks using the discrete element method. It was shown that the method was able to reproduce important phenomena such as crack opening and joint sliding. Formica *et al*., [15] presented a discrete mechanical model for masonry walls based on a Lagrangean description where each brick is described as a rigid body and each mortar joint as an interface element. Morbiducci [16] investigated the parameter estimation problem for brick masonry models. An identification procedure was proposed in which the uncertainties of known parameters and/or errors of measurements were main elements of distinction. Calio *et al*., [17] proposed a simplified model for the evaluation of the seismic behavior of masonry buildings. The reliability of the proposed model had been evaluated by means of non-linear push-over analyses performed on masonry walls for which both theoretical and experimental results were available. Bothara *et al*., [18] developed a linear elastic finite element model using four-node shell elements for walls in SAP2000. Penna *et al*., [19] suggested that with the recent research advances and availability of computational tools based on frame type macro-element modeling the consistent evaluation of the seismic performance of masonry building is possible. Pena *et al*., [20] proposed a 3-D solid model in the finite element software DIANA. They presented a simple strategy of analysis for seismic assessment of the Qutub Minar in Delhi, India. Ghiassi *et al*., [21] presents a macro-computational model for simulating the nonlinear static behavior of masonry walls. The adopted strategy was based on modeling the nonlinear behavior of

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masonry elements considering it as an orthotropic material and then extending it with a simple method to masonry walls.

2) Experimental work done to evaluate masonry properties

Dhanasekra *et al.*, [22] derived a non-linear stress-strain relation for brick masonry. Relations were obtained from the results of a large number of biaxial tests on half-scale square panels with various angles of the bed joint to the principal axes. Ali and Page [23] developed a method of finite element analysis for solid masonry subjected to in-plane loading. Two different collapse models were used in the finite element program to simulate the post cracking behavior of the masonry. Naraine and Sinha [24], [25] conducted an experimental program to study the behavior of brick masonry under cyclic compressive loading. Further they discussed the reloading and unloading stress-strain curves of brick masonry tested under uniaxial cyclic compressive loading perpendicular and parallel to the bed joint in the same year. Sarangapani *et al.*, [26] worked on the characterization of properties of local low modulus bricks, mortars and masonry. Kaushik *et al.*, [27], [28] conducted the comprehensive experimental study and determined the comprehensive stress-strain relationship for masonry. An analytical model was proposed to adequately plot the stress-strain curves for masonry using the six control points on the curve. A simplified model was also proposed that can be continuously used in FEM programs. Ali *et al.*, [29] correlated the mechanical properties of masonry with mortar type, masonry strength and mix proportion. Also they established the simplified relationships which were helpful in the design of masonry structures under wind and earthquake induced lateral loading.

II. Modeling of Masonry Wall

A. Material Modeling of Masonry Wall

A homogeneous modeling approach is applied. In the homogeneous modeling approach the test results and analytical curve suggested by Kaushik *et al.*, [27], [28] are adopted. The details are given in Section IV.

B. Geometric Modeling of Masonry Wall

In the present study a 3mx3m free standing wall fixed at its end is considered. The thickness of wall is 200mm. A vertical working load of 20kN/m is considered on the wall. The wall is designed manually for the above load. All the stresses (tensile and shear) are found within the permissible limit as per IS1905:1987 [30].

C. Modeling in SAP 2000 Software

In order to model the wall in SAP2000 we use shell area element. In SAP 2000 the shell element is a three or four node formulation that combines separate membrane and plate-bending behavior. The shell element can be of two types homogenous and shell layered. In the present study the layered shell area element is considered in order to obtain full shell behavior.

III. Verification of Model in SAP 2000 Software

The present work uses both linear and non-linear shell element. The model is validated by increasing the mesh size from 1x1, 2x2, 4x4, 8x8, 16x16 and 32x32 respectively. While on the other hand a lateral force of 100kN is taken. The manually calculated deformations (displacements) are compared with the software results. The deformation values for different mesh size and lateral loadings are shown in Table I and Table II respectively. The non-linear shell element is used while performing push-over analysis.

TABLE I. Shell Layered Linear Displacement for a Lateral Load of 100KN

Panel Type	Displacement (10^{-3}m)	
	Theoretical calculated displacement 1.542	
	Left Hand Node (4)	Right Hand Node (3)
Panel without meshing	1.10	1.21
2x2 Panel	1.35	1.37
4x4 Panel	1.52	1.53
8x8 Panel	1.58	1.59
12x12 Panel	1.59	1.60
16x16 Panel	1.59	1.60
20X20 Panel	1.59	1.60
24x24 Panel	1.59	1.60
28x28 Panel	1.59	1.60
32x32 Panel	1.59	1.60

TABLE II. Shell Layered Non-Linear Displacement for a Lateral Load of 100KN

Panel Type	Displacement (10^{-3}m)	
	Theoretical calculated displacement 1.542	
	Left Hand Node (4)	Right Hand Node (3)
Panel without meshing	1.92	1.92
2x2 Panel	2.12	2.21
4x4 Panel	2.46	2.46
8x8 Panel	2.55	2.55
12x12 Panel	2.57	2.57
16x16 Panel	2.58	2.58
20X20 Panel	2.58	2.58
24x24 Panel	2.58	2.58
28x28 Panel	2.58	2.58
32x32 Panel	2.58	2.58

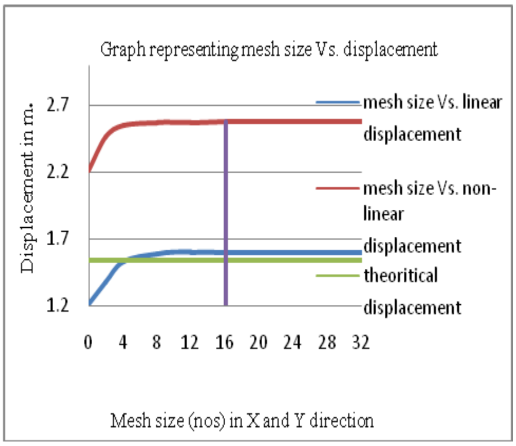

Figure 1. Graph representing mesh size vs. displacement.

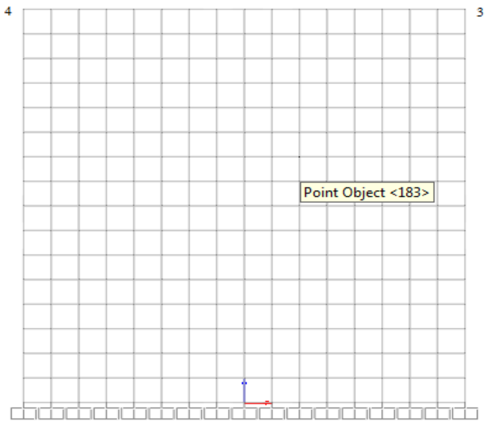

Figure 2. Modeling of masonry wall in 16x16 mesh size

IV. SELECTION FOR MESH SIZE OF MASONRY MODEL

From Table I, Table II and Fig. 1 it is observed that for a lateral load of 100kN the percentage difference between theoritically calculated and software calculated deformation values for 1x1, 2x2, 4x4, 8x8, 16x16 and 32x32 panel size's are 21.53%, 11.15%, 1.45%, 2.46%, 2.46% and 2.46% respectively. While the difference between linear and non-linear deformations for the same panel sizes are 37.19%, 43.07%, 43.42%, 43.67%, 42.76% and 42.76% respectively. Thus from the above discussion the following sailent features were observed-

- On moving towards higher meshing the percentage difference between calculated lateral deformation and software results are reducing i.e. higher meshing increases the acuuracy of result. Thus satisfying the principle of finite element method.
- The percentage difference between calculated lateral deformations and software lateral deformations are almost same for 16x16 and 32x32 finite element meshing of masonry wall.
- The percentage difference between linear lateral deformation and non-linear lateral for all loads as calculated by SAP 2000 were also same for 16x16 and 32x32 mesh sizes.
- Thus for further analysis of masonry wall 16x16 mesh size masonry wall has been selected.

V. NONLINEAR STATIC (PUSHOVER) ANALYSIS OF MASONRY WALL

A pushover analysis is a non-linear static procedure wherein monotonically increasing lateral loads are applied to the structure till a target displacement is achieved or structure is unable to resist further loads. For the pushover analysis the procedure given by FEMA 356 is adopted [31].

A. Material Modelling of Masonry Wall

A homogeneous modeling approach is applied. The masonry units, mortar elements are assumed to be smeared and considered isotropic. In the homogeneous modeling approach the test results and analytical curve suggested by Kaushik *et al*., [27], [28] are adopted. For the pushover analysis in the selected masonry wall model (16x16 finite element mesh size as shown in Fig. 2) three different properties of masonry with weaker, intermediate and strong mortar as evaluated are used. For each set of masonry two sets of stress-strain values are taken from analytical curve. The stress values are taken up to 0.25 f'_m (as per IS1905:1987 [30]) and 0.33 f'_m (as per ACI 530-02 code [32]). On the other hand the strain values are taken up to 0.003 levels. As per IS1905:1987 [30] the tensile stress is taken up to 70kN/m^2. But in our case considering the bending also the permissible tensile stress is taken as 45kN/m^2 (as obtained from experimental results by Ali *et al*., [29]). Fig. 3 and Fig. 4 shows the two stress-strain model considered for analysis.

- Masonry 1 and Masonry 2
  Masonry 1 and Masonry2 are the properties of masonry with weaker mortar and stress value taken upto 0.25 f'_m and 0.33 f'_m respectively. For weaker mortar the various parameters considered are shown in Table III.

TABLE III. PARAMETERS CONSIDERED FOR MASONRY 1 AND MASONRY 2

Parameters	Masonry 1	Masonry 2
Prism strength (f'_m)	1025kN/m^2	1425kN/m^2
Modulus of elasticity.	563.7x10^3kN/m^2	798.6x10^3kN/m^2
Poisson's Ratio	0.25	0.25
Coefficient of expansion	5.5x10^{-6}	5.5x10^{-6}
Modulus of rigidity (G)	225.5x10^3kN/m^2	319.4x10^3kN/m^2
Weight per unit Volume (W)	20kN/m^2	20kN/m^2
Density (p)	2.038	2.038

- Masonry 3 and Masonry 4
  Masonry 3 and Masonry 4 are the properties of masonry with intermediate mortar and stress value taken upto 0.25 f'_m and 0.33 f'_m respectively. For intermediate mortar the various parameters considered are shown in Table IV.

TABLE IV. PARAMETERS CONSIDERED FOR MASONRY 3 AND MASONRY 4

Parameters	Masonry 3	Masonry 4
Prism strength (f'_m)	1650kN/m	2178kN/m^2
Modulus of elasticity.	907.5x10^3kN/m^2	1198x10^3kN/m^2
Poisson's Ratio	0.25	0.25
Coefficient of expansion	5.5x10^{-6}	5.5x10^{-6}
Modulus of rigidity (G)	363x10^3kN/m^2	479.2x10^3kN/m^2
Weight per unit Volume (W)	20kN/m^2	20kN/m^2
Density (p)	2.038	2.038

TABLE V. PARAMETERS CONSIDERED FOR MASONRY 5 AND MASONRY 6

Parameters	Masonry 5	Masonry 6
Prism strength (f'_m)	1875kN/m^2	2475kN/m^2
Modulus of elasticity.	1031x10^3kN/m^2	1361x10^3kN/m^2
Poisson's Ratio	0.25	0.25
Coefficient of expansion	5.5x10^{-6}	5.5x10^{-6}
Modulus of rigidity (G)	412.5x10^3kN/m^2	544.5x10^3kN/m^2
Weight per unit Volume (W)	20kN/m^2	20kN/m^2
Density (p)	2.038	2.038

- Masonry 5 and Masonry 6

Masonry 5 and Masonry 6 are the properties of masonry with stronger mortar and stress value taken up to 0.25 f'$_m$ and 0.33 f'$_m$ respectively. For intermediate mortar the various parameters considered are shown in Table V.

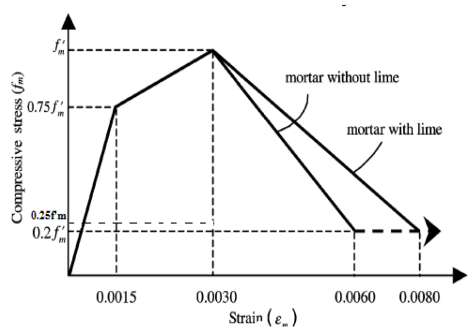

Figure 3. Stress-strain model taken upto 0.25f'm as per IS 1905:1987.

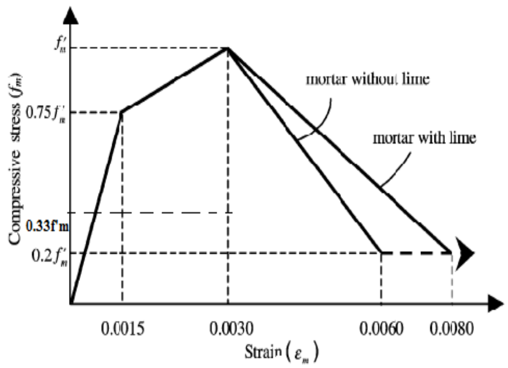

Figure 4. Stress-strain model taken upto 0.33f'm as per ACI 530-02.

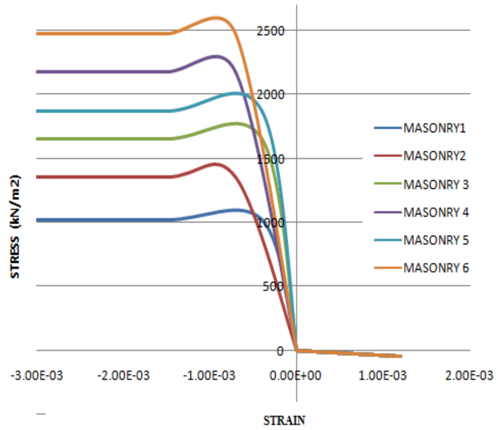

Figure 5. Graph representing stress-strain curve for different masonry.

B. *Outcome of Pushover Curve*

The salient features observed from the pushover curves (Fig. 6 to Fig. 11) are illustrated as follows-

- For weaker mortar

  For masonry wall having property masonry 1 and masonry 2 the target base shear values are 145.65kN and 182.95kN respectively. While the target displacement values comes to be as 0.0023m and 0.0018m respectively.

- For intermediate mortar.

  For masonry wall having property masonry 3 and masonry 4 the target base shear values are 183.61kN and 269.82kN respectively. While the displacement values are 0.0013m and 0.0051m respectively.

- For stronger mortar.

  For masonry wall having property masonry 5 and masonry 6 the target base shear values are 260.37kN and 268.75kN respectively. While the displacement values are 0.0059m and 0.0045m respectively.

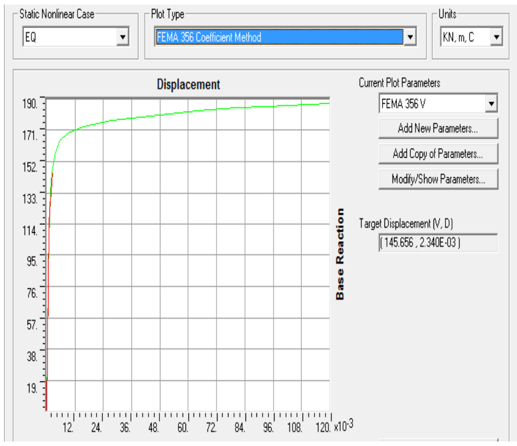

Figure 6. Performance point for property 1 as per FEMA-356.

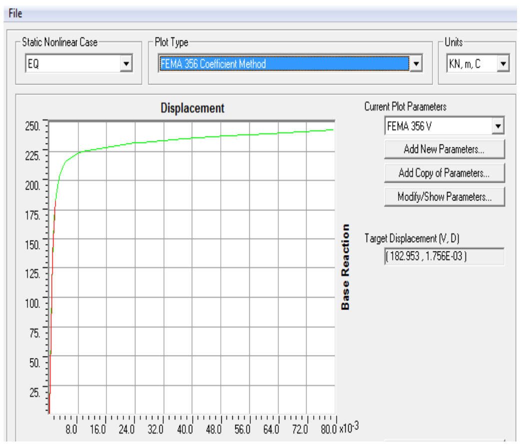

Figure 7. Performance point for property 2 as per FEMA-356.

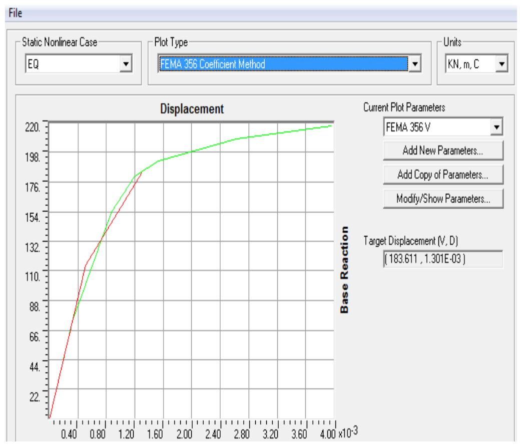

Figure 8. Performance point for property 3 as per FEMA-356.

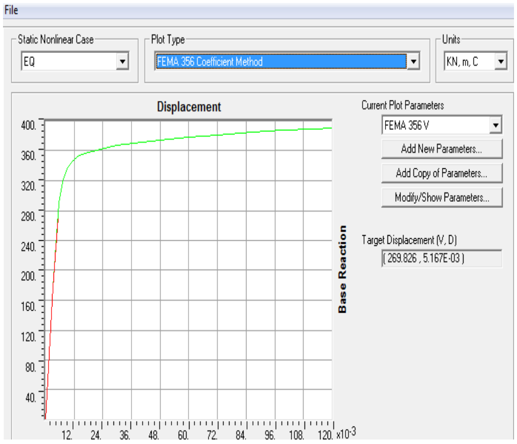

Figure 9. Performance point for property 4 as per FEMA-356.

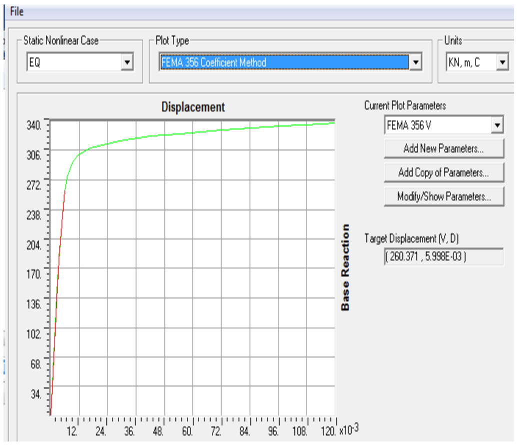

Figure 10. Performance point for property 5 as per FEMA-356.

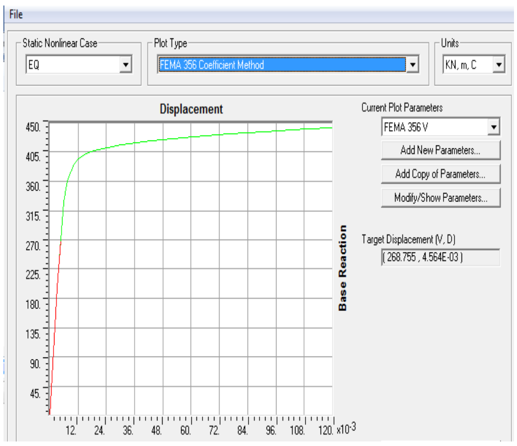

Figure 11. Performance point for property 6 as per FEMA-356.

VI. Conclusion

From the pushover curve of different properties the following observations are made-

- For masonry with weaker mortar as the stress level increases from 0.25 f'$_m$ to 0.33 f'$_m$ the base shear increases by 40.98% while the displacement decreased by 24.95%.
- For masonry with intermediate mortar as the stress level increases from 0.25 f'$_m$ to 0.33 f'$_m$ the base shear increases by 46.95% but the displacement is increased by 297.15% thus more ductile behavior is observed as compared to stronger mortar. Thus confirms the experimental result of Kaushik *et al.*, [27], [28].
- For masonry with stronger mortar as the stress level increases from 0.25 f'$_m$ to 0.33 f'$_m$ the base shear increases by 3.21% but the displacement is reduced by 23.97 % .
- Since the value of base shear is more for intermediate mortar in comparison to weaker mortar and almost equal in comparison to stronger mortar. Also increase in displacement percentage on moving from 0.25f'$_m$ to 0.33 f'$_m$ is higher in case of intermediate mortar in comparison to weaker and stronger mortar. Thus the intermediate mortar performance is better in comparison with weaker and stronger mortar.

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