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Technique for Non-Linear Analysis of Masonry Wall Using Discrete Crack Finite Element Method

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Abstract

Nepal has experienced a number of great earthquakes in different periods including a recent Gorkha Earthquake 2015. A large destruction has occurred in those earthquakes to the structures constructed in different locations in Nepal. As Nepal is a developing country, masonry buildings with cement-sand mortar or mud mortar is very common due to economy and availability of construction material. Destruction due to earthquake is more in the case of masonry structure because of lack of proper methods and technique for precise analysis tool. In the last decades, a new line of research has been defined in the field of earthquake engineering, trying to implement nonlinear structural analysis in order to give more accuracy and safety to buildings and consistency between the analysis and design methods. In this new line of research, "pushover curve" of a structure is a very important element to be obtained. At present, a lot of research has been made to characterize the non-linear structural behavior of masonry structure however a clear model to describe the nonlinear behavior of masonry structure is not yet developed. In this paper, a numerical method to characterize the nonlinear in-plane behavior of masonry wall under lateral load is developed. The main product of this study is a technique or method for obtaining nonlinear "pushover curve" for a masonry structure using finite element method.

Keywords

Masonry Structures, Non-Linear Analysis, Pushover Curve

1. Introduction

Nepal has experienced a number of great earthquakes in different periods including a recent Gorkha Earthquake 2015. A large destruction is occurred in those earthquakes to the structures constructed in different locations in Nepal. As Nepal is a developing country, masonry buildings (brick or stone) with cement-sand mortar or mud mortar is very common due to economy and availability of construction materials. Rapid and unmanaged development of Nepal has led to the construction of buildings without proper engineering design, ductile detailing to improve seismic resistance, poor construction material and quality control which further led to the great extent of damage in recently occurred earthquake.

Most of the Masonry buildings built in Nepal are not according to the code requirements. Such buildings when subjected to earthquake may not resist the seismic loads coming into them. So, it is necessary to check the building whether they are seismically efficient or not by analyzing their seismic performance in existing condition.

Taking these facts into account, it is clear that more research and development about the mechanical properties and structural performance of masonry is needed, in order to improve its safety against seismic demands.

In the last decades, a new line of research has been defined in the field of earthquake engineering, trying to implement non-linear structural analysis in order to give more accuracy and safety to buildings and consistency between the analysis and design methods. In most of these new methods, the "pushover curve" of a structure is a very important element to be obtained.[1]

Unfortunately, for masonry there is still no clear model to describe the nonlinear behavior of this material, because of its complexity and wide variety of forms and, therefore, it is not easy to determine the "pushover curve" of a masonry structure[1]. In this paper, a numerical method to characterize the in-plane behavior of masonry under lateral loads is developed. The main outcome of this numerical model is the pushover curve of a masonry wall.

In this paper, a technique for determination of non-linear analysis is performed considering the assumed crack and performing non-linear analysis using finite element method. Even though, many attempts have been made for the determination of non-linear analysis of masonry wall using finite element method, consideration of assumed cracked surface using finite element analysis and hence non-linear analysis of the structure using discrete crack modeling haven't been performed until the time of this research, the technique for non-linear analysis in this study is considered novel technique.

2. Methodology

According to many authors, there are many different possibilities for the modeling of masonry walls. In this study, unreinforced masonry wall (URM) is modeled using Finite Element Modelling in a Finite Element Software (SAP2000). A failure plane is initially assumed at a certain angle with the horizontal and the non-linear material properties (tension, compression and shear) of the masonry wall at the failure surface are assigned through the nonlinear links that are assigned at a certain spacing along the assumed fracture plane. During nonlinear analysis,the nonlinear force-deformation relationships are used at all degrees of freedom for which nonlinear properties are specified.The nonlinear compression force is assigned according to Hemant Kaushik [2].The nonlinear tensile strength of the wall is calculated according to Dhansekar and Haider using the experimental value of tensile strength [3]. The shear strength behavior along the failure surface is obtained using the Mohr-Coulomb Theory. Thus obtained nonlinear tensile, compressive and shear strength parameters are applied along the assumed cracked surface and nonlinear analysis is performed. In this way, we obtain the nonlinear pushover curve for a particular failure surface. However, the actual failure may not have taken along the assumed failure surface. From the area under the non-linear force-displacement curve, we can obtain the amount of energy required for the failure of the wall along that plane[4]. The above process is repeated for various failure surfaces and the failure surface along which the amount of energy required for failure is minimum is actual failure surface and the corresponding nonlinear curve is the nonlinear curve for the proposed masonry wall.

As the wall fails by either tension, shear or the combination of both, the nonlinear behavior of the masonry wall can be obtained using the tensile strength, cohesion and friction coefficient of the mortar. In order to validate the result, wall model whose lateral force vs displacement was experimentally obtained by Raijmaker [5] was numerically analyzed using Finite Element Analysis.

Experimental Model

For the validation of the model, experiments on solid walls carried out by Raijmakers (1992) were considered. The test was done on a specimen consisting of a pier with a width/height ratio of one (990x1000 mm2), built up with 18 layers (16 layers unrestrained) of solid clay bricks (dimensions 204x98x50 mm) and 10 mm thick mortar (1:2:9, cement: lime: sand by volume). The piers were subjected to different vertical compression forces P before a horizontal load was monotonically increased under top displacement control until failure. [5]

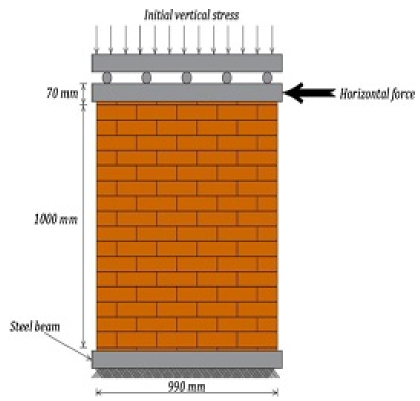

Figure 1: Experimental Wall used for Validation of Proposed Method Raijmaker(1992)

All parameters used in this verification study are summarized in the table below:

Table 1: Elastic Properties of Constitutive Material and Joints Properties

S.No	Elastic Properties	Masonry Constitutive	Solid Wall J4D and J5D
1	Elasticity	Brick(E_u) (MPA)	16700
		Mortar(E_m) (MPA)	780
		Expanded Units (MPA)	4050
2	Poisson Ratio	Brick/Mortar	0.15
3	Joint Stiffness	$K_{nn}(N/mm^3)$	82
		K_{ss},$K_{tt}(N/mm^3)$	36

Table 2: Non-Linear Material Properties for the joint interface

S.No	Non-Linear Properties Interface		Solid Wall J4D and J5D
1	Tension	$t_n^{max}(MPA)$	0.25
2	Shear	$C(MPA)$	1.4 t_n^{max}
		μ	0.75
		G_{II}^{f} (N/mm)	0.125
3	Compression	$\sigma_c(MPa)$	10.5

Numerical Model Description

Finite Element Software SAP2000 provides a platform for the modeling of the wall at a macro level and by assigning the spring properties along the fracture surface, micro-level of analysis can be performed along the fractured surface. For our study, 2D Shell Element modeling is performed to model a masonry wall. The linear elastic properties of the masonry wall like Modulus of Elasticity, Poisson's ratio, the Unit weight of the brick masonry are provided. Multilinear elastoplastic spring is assigned at various locations along the assumed crack surface and the nonlinear force-displacement relation along with tension, compression and shear are provided along with the multilinear elastoplastic springs. The pre-compression load is applied in the direction of gravity at the top of the wall and lateral load is increased gradually at the top of the wall in X Direction.

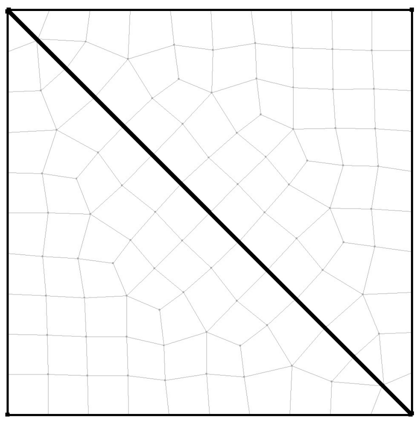

Figure 2: Numerical Modelling of Masonry Wall with assumed crack plane at 45 degree

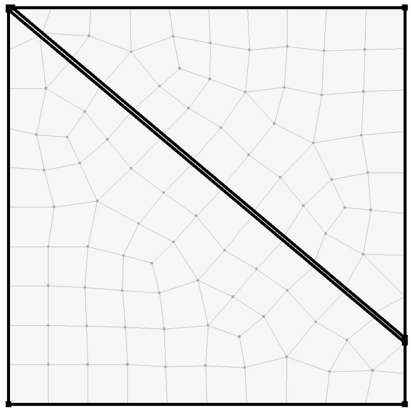

Figure 3: Numerical Modelling of Masonry Wall with assumed crack at 40 degree, rotation about top joint

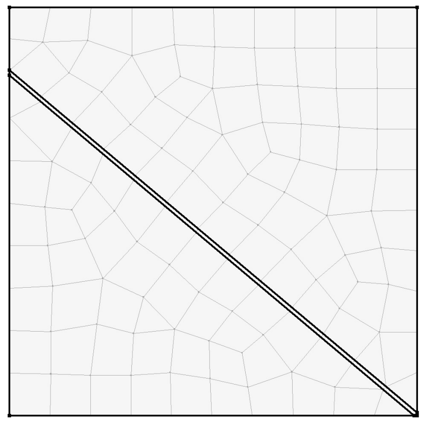

Figure 4: Numerical Modelling of Masonry Wall with assumed crack at 50 degree, rotation about bottom joint

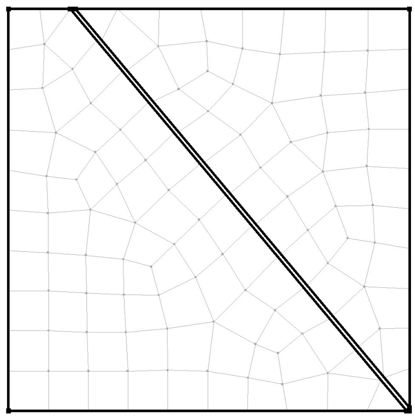

Figure 5: Numerical Modelling of Masonry Wall with assumed crack at 50 degree, rotation about bottom joint

Material Properties The nonlinear material properties are obtained from calculation using the value of cohesion and friction coefficient along with vertical stress which are used to model the wall with nonlinear links through the assumed cracked surface. The nonlinear link describes the linear and nonlinear behavior for the link object to which they are assigned. Multilinear plastic link has been created and the nonlinear tensile, compressive and shear Force vs Displacement relation is provided along the nonlinear link. A typical force vs displacement relation assigned for a particular spring in tension, compression and shear is shown in Figure 6

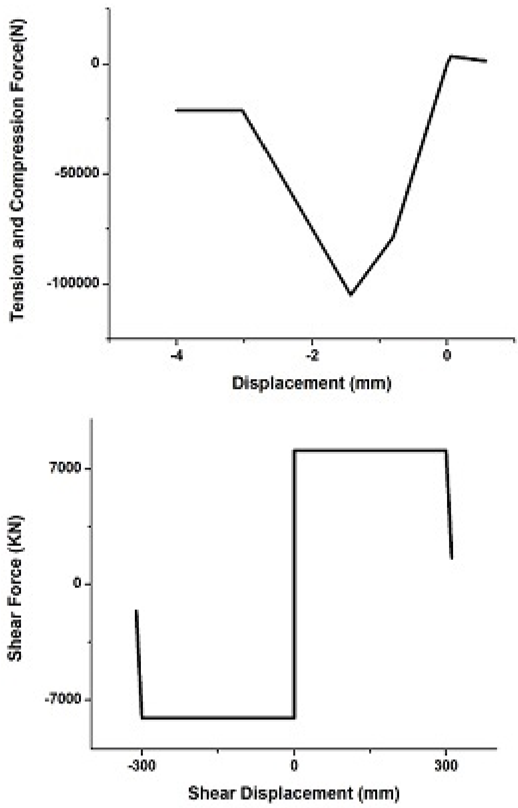

Figure 6: Typical Tension, Compression and Shear Force Vs Displacement behaviour assigned to various nonlinear links

3. Result and Analysis

Based upon the nonlinear analysis of masonry wall using various assumed fracture plane, nonlinear force vs displacement graphs are obtained for various orientation of fractured plane i.e at 40°,50°,45°, etc. The non-linear force displacement relation which are obtained by assigning non-linear link properties to the link along the assumed fracture plane is shown in Figure 8.

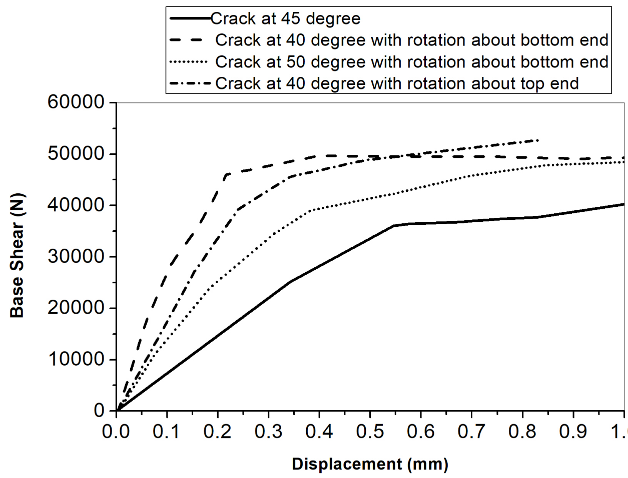

Figure 7: Force Displacment Graph for Various Assumed Fracture Plane

The amount of energy dissipated by the structure can be obtained by the area under the curve. For a particular displacement of 1 mm, it can be clearly seen that the area under the curve obtained by assuming fracture plane at an angle of 45° is minimum. Hence, we can say that fracture in the masonry wall for the given condition of loading is along 45° plane.So, we take the modelling and analysis of masonry wall for crack at 45° only. Now, the obtained nonlinear force vs displacement relation is compared with experimental result[4] in Figure 9. The pushover curve obtained numerically from the proposed model is compared with the experimental result by Raijmaker [5]. In Figure 8, we have consider the non-linear force displacement relation for various curve for displacement of 1 mm only as because of numerical unstability in Finite Element Software, analysis could not run beyond certain value.Since, the theoretical framework is verified with the considered result, we limit the displacement upto 1 mm and took energy dissipated during the application of lateral force.

In Figure 9, the nonlinear force displacement relation from the finite element analysis is compared with experimental result which was obtained by Raijmaker [5]. Raijmaker in his work has performed experiment with precompression load of 0.3,1.21 and 2.12 MPa. Out of these, for this study we have taken 0.3 MPa because we are trying to study the diagonal shear failure pattern for lower pre-compression load. The initial slope of both curve is almost same i.e. we have precisely predicted the initial stiffness of the masonry wall. The graph from the proposed model can be compared with the experimental graph in terms of peak displacement, load at peak displacement and area under the curve as in Table 3.

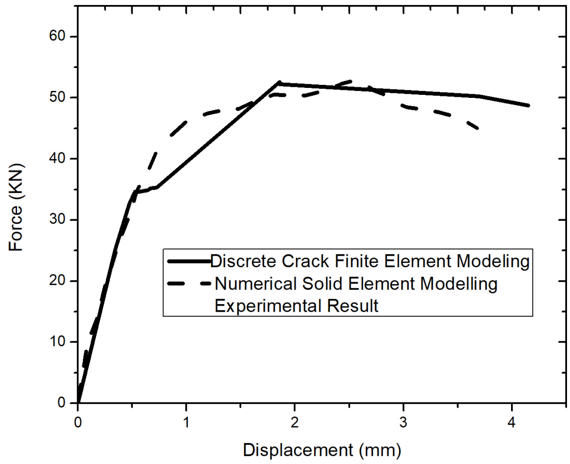

Figure 8: Force Vs Displacement Graph from Raijmaker Experimental Result and Proposed Finite Element Method

Table 3: Comparision of Result from experimental and Proposed Force Displacement Curve

	Result from Proposed Method	Experimental Result
Peak Displacement (mm)	4.2	3.8
Load at Peak Displacement (KN)	45	48
Area under the Curve (AUC) (KNmm)	170.768	162.255

4. Conclusion

In this study, a new technique for nonlinear analysis of masonry wall using discrete crack finite element method is proposed and validated using the experimental result. Some of the major points that we obtain through this study are:

- For a pre-compression load of 0.3 MPa, when the lateral load is applied in the considered wall, diagonal crack occur in the wall at an angle of 45°.
- The initial stiffness from experimental result almost coincide with the value from proposed method 70 KN/mm
- Area under the curve from two methods are almost same; 170.768 KNmm from theoretical result and 162.255 KNmm from experimental result; which shows the amount of energy dissipated during the loading.
- We can obtain the nonlinear behavior of a masonry wall based upon it's nonlinear tensile, compressive and shear strength parameter.

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