CAPACITY INTERACTION CURVES FORMASONRY WALLS UNDER BIDIRECTIONALSEISMIC LOADING

Mahmoud Reza MAHERI
Professor, Department of civil and environmental engineering, Shiraz University, Shiraz, Iran
maheri@shirazu.ac.ir

M. Amir NAJAFGHOLIPOUR
Assistant professor, Department of civil and environmental engineering, Shiraz University of Technology, Shiraz, Iran
najafgholipour@sutech.ac.ir

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ABSTRACT

During an earthquake a wall is subjected to a three dimensional acceleration field and undergoes simultaneous in-plane and out-of-plane loading. The presence of one type of loading on a structural element affects the strength of that element against another type of loading. A considerable number of numerical and experimental studies, carried out to-date to investigate the behaviour of masonry walls under seismic loading, have considered the in-plane or the out-of-plane response of the wall separately without due consideration for any possible interaction between the two responses. In this paper, the results of a series numerical parametric studies are carried out on full scale unreinforced masonry walls are presented. The considered parameters are material properties of masonry and aspect ratio of the walls. Current study is in continuing of the previous experimental and numerical studies carried out by authors before. The parametric studies indicate that the material properties and aspect ratio of the walls has considerable effects of interaction curves of masonry walls. Also the elastic material properties and inelastic material properties in tension are more effective on the in-plane and out of plane loads interaction in masonry walls.

INTRODUCTION

A brick wall undergoing an earthquake global acceleration field is subjected to both in-plane and out-of-plane loads. The former results from the storey shear force under horizontal loading and the latter is either due to the out-of-plane inertia force caused by the considerable mass of the brick wall or the out-of-plane action of a flexible floor on the wall. In previous experimental and numerical studies carried out by authors (Najafgholipour et al, 2013), the results show interaction between in-plane and out of plane loads in unreinforced masonry panels. To complete the results and to investigate the effects of different parameters such as material properties of the masonry and aspect ratio of the wall on the in-plane and out of plane interaction curve of unreinforced masonry walls, a numerical parametric study is carried out and the results are presented in this paper.

Considerable experimental, numerical and analytical studies have been carried out on the behaviour of masonry buildings, particularly under earthquake loading and mostly on the behaviour of brick walls. Most of the researches are carried out on in-plane or out of plane behavior of unreinforced masonry walls without existence of the other loading type.Very few studies were carried out on the numerical response under simultaneous in-plane and out-of-plane loading. Shapiro et al (1994) studied the interaction of the in-plane and out-of-plane responses of brick infills in concrete frames. They carried out a series of tests to investigate the effects of in-plane cracks on the out-of-plane strength. Their test results showed that the in-plane cracks may reduce the out-of-plane strength of infills up to 100%. A similar experimental study was carried out by Falangan et al (1999) on brick infills in steel frames. Recently, Hashemi and Mosalam (2007) conducted an in-plane shake table test on a concrete infilled frame, subsequently used to calibrate a numerical model that was further developed to include out-of-plane loading.

In this paper at first the numerical method used here is introduced and the method is verified by comparing the results with the previous experimental results. Then,a series of parametric studies are carried out and the results are presented and discussed.

NUMERICAL STUDIES

In this section, the results of a numerical study aimed at evaluating the in-plane and out-of-plane interaction curves for full scale brick walls are presented. For this propose, results obtained from the experiments discussed in the previous article by authors (Najafgholipour et al, 2013) are first utilized to validate the numerical models adopted. The interaction curves are then evaluated numerically for full scale brick walls having three different aspect ratios (Height/Length) of 0.5, 1 and 2 and with different material properties.

Due to the complex in-plane and out-of-plane loading, for numerical modeling of the test panels, suitable continuum macro model based on anisotropic plasticity is adopted (Lourenco, 2000) for the three dimensional analysis of brick walls. This material model is implemented in software Diana V9.4 via a user supplied subroutine.

The adopted composite yield criterion in this model is based on the plane stress anisotropic yield criterion of Lourenço et al (1997), in the typical five stress component space, with two normal stresses σ_x and σ_y and three shear stresses $\tau_{\tau xy}$, τ_{yz} and τ_{xz}. The composite yield criterion includes a Hill type criterion for compression and a Rankine type criterion for tension (Fig. 1).

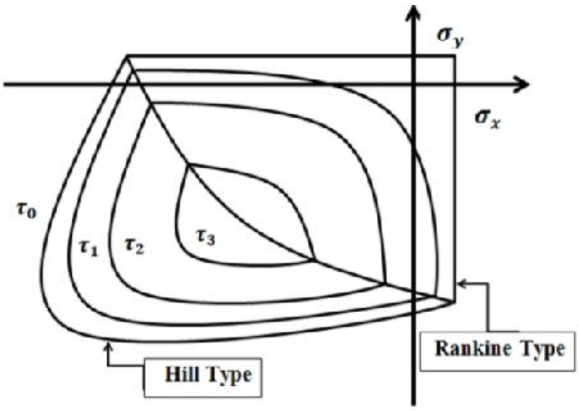

Figure 1.The plane stress anisotropic yield criterion (Lourenco et al, 1997)

In total, nine elastic and twelve inelastic parameters are needed in Diana software to compose the proposed anisotropic material model. The elastic parameters are the Young's modulus, E, the Poisson's ratio, ν and the shear modulus, G, of the anisotropic material. The inelastic parameters for tension regime are the tensile strength along *x* and *y* directions (f_{tx} and f_{ty}), the fracture energies in tension along *x* and *y* directions ($G_{fx}$and G_{fy}) and parameter α. The inelastic parameters in compression are the compressive strength along *x* and *y* directions (f_{cx} and f_{cy}), the fracture energies in compression along *x* and *y* directions ($G_{fcx}$and G_{fcy}), the parameters β and γ, and the parameter k_c that represents the equivalent plastic strain at peak compressive strength.

Verification of the numerical model

The Diana software's layered shell element (CQ40L) with seven Simpson integration points along the height is used for modeling the test panels subjected to combined loading. The material parameters used in the models are derived from the materials tests, from literature (see Lourenco, 2009) and from the pure shear and bending tests. The material parameters used for these studies are listed in Table 1.

Similar to tests discussed by Najafgholipour et al (2014), the masonry panels were subjected to three different types of loading. These included pure in-plane diagonal compressive force, pure out-of-plane point load and simultaneous in-plane and out-of-plane loading, Fig. 2. The load-displacement curve obtained from the numerical analysis of the brick panel under in-plane loading is compared with that obtained from the experiments in Fig. 3-a. Similar comparisons are made for the numerical and experimental results of the panel under out-of-plane loading in Fig. 3-b. Comparisons of the load-displacement curves obtained from the tests and the numerical studies show good agreements between the results in both cases.

Table 1- Material properties of masonry used for numerical studies of brick panels

Elastic parameters

Young's modulus (MPa)			Poisson's ratio			Shear modulus (MPa)		
E_x	E_y	E_z	υ_{xy}	υ_{xz}	υ_{yz}	G_{xy}	G_{xz}	G_{yz}
12000	8000	12000	0.2	0.2	0.2	3200	3200	3200

Inelastic parameters in tension regime

f_{tx}(MPa)	f_{ty}(MPa)	G_{fx}	G_{fy}	α
1.5	0.25	0.08	0.007	1.35

Inelastic parameters in compression regime

f_{cx}(MPa)	f_{cy}(MPa)	G_{fcx}	G_{fcy}	β	γ	k_c
4.0	8.0	5.0	10.0	-1.0	10.0	0.0005

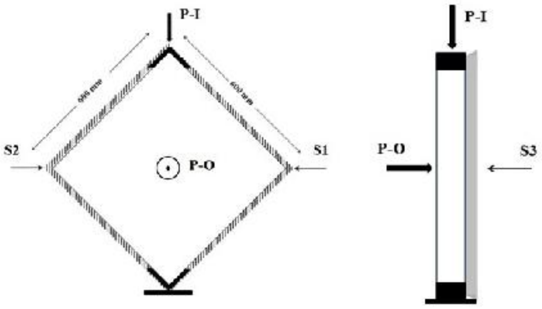

Figure 2.Test set up for in-plane and out of plane loading of panels

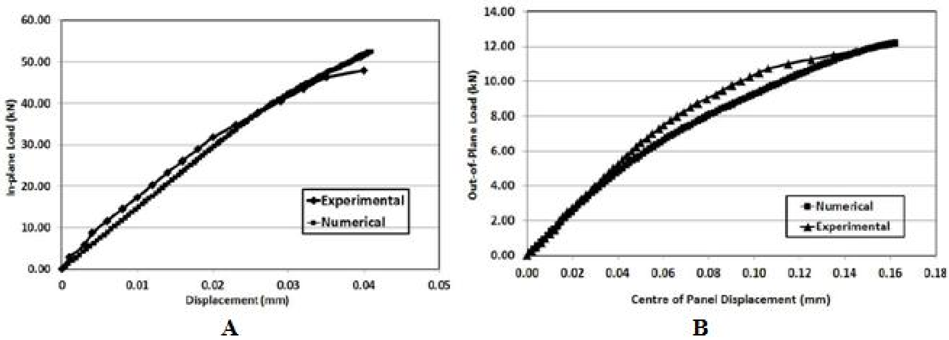

Figure 3.a- In-plane load-displacement curves of masonry panels, b-Out-of-plane load-displacement curves of masonry panels

The normalized numerical interaction curve for the panel undergoing different levels of simultaneous in-plane and out-of-plane loading is compared with the interaction curve obtained from the experiments in Fig. 4. This figure also shows that the numerical model used can predict well the in-plane shear, out-of-plane bending capacity interaction in brick masonry walls. The difference between experimental and numerical results is below 10% and the numerical results in the central part of the interaction curve are conservative.

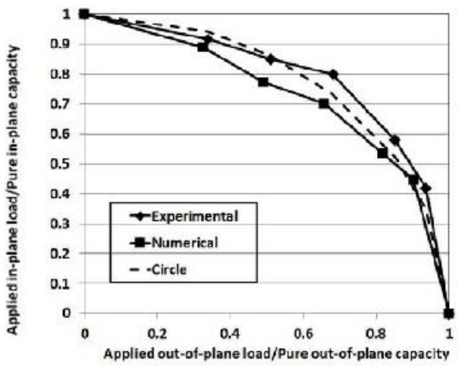

Figure 4. Normalised in-plane, out-of-plane capacity interaction curves for the brick panels

PARAMETRIC STUDIES

To investigate the influences of material and geometrical properties of the walls on the in-plane and out of plane loads interaction in full scale unreinforced masonry walls, a series of parametric numerical studies are carried out and the results are presented in the following sections. The parameters can be put into two categories such as material properties of the masonry and aspect ratio of the wall. The numerical studies are done in software DianaV9.4 and with the procedure described in the previous section.

Aspect ratio effects

Three different walls with dimensions of 3m×6m, 3m×3m and 6m×3m, respectively, corresponding to aspect (height/length) ratios of 0.5, 1 and 2, are investigated. Similar to the brick panels, the full-scale walls were one brick thick. Nonlinear analyses of the walls under pure in-plane and out-of-plane loads were first carried out and their respective capacities were determined. The out-of-plane load was now applied in a uniformly distributed way on the entire area of the wall, to better represent the seismic action. The in-plane load was applied horizontally at the top of the wall in a 20 cm depth.

. After the pure in-plane and out-of-plane capacities of the walls were established, the walls were subjected to simultaneous loading and their interactive capacities were determined. Loading of the walls was carried out in the same manner as that carried out for the brick panel; i.e. a specific amount of constant out-of-plane load was first applied to the wall, followed by the incremental application of the in-plane load until the wall failed.

The normalized interaction curves obtained for the walls with the three different ratios are plotted in Fig. 5. A strong capacity interaction can be observed whereby the presence of the out-of-plane load causes reduction in the in-plane capacity of the wall and vice-versa. The interaction is particularly strong at higher loads and the shapes of the interaction curves in the three walls are different, indicating the influence of the wall’s aspect ratio on the interaction. The effect of out-of-plane load on the in-plane shear capacity is the lowest for the wall with H/L = 0.5 and is the highest for the wall with H/L = 2.0. This can be attributed to the fact that the critical bending (bending perpendicular to the bed joints) is less relevant in slender (tall) walls.

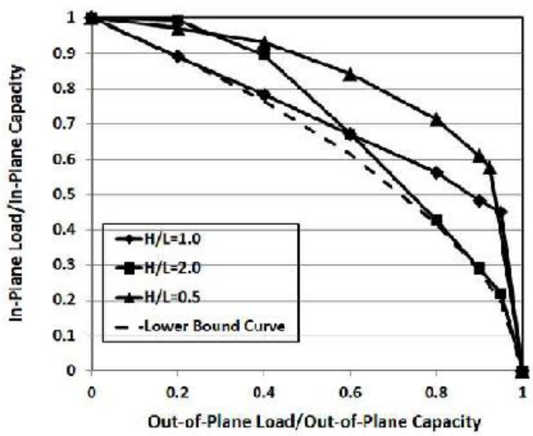

Figure 5.Normalised interaction curves for full scale walls with three different aspect ratios

Material properties effects

The results obtained in previous section for full scale masonry walls were based on the material properties of the test panels. Surely the mechanical properties of the masonry can affect the in-plane and out of plane interaction of masonry walls as well as the aspect ratio. Due to the material model which is used in current numerical studies and the required parameters for linear and nonlinear analyzes, in this section the results of a series of sensitivity analyzes for investigation of the effects of the material property values on the in-plane and out of plane loads interaction in unreinforced masonry walls are presented.

In current parametric studies, except the parameter which it's effects on the interaction is required, all of the other material properties are kept constant. In this way the difference in the interaction curves in each section is only due to the variable parameter. It is noted that the base material properties of the walls in the parametric studies are equal to the values of the masonry used in test panels. The analyses are carried out for the square wall. The boundary conditions, loading types and analysis procedure are similar to the geometrical parametric studies on full scale walls described in previous section.

The values of the material properties used for the current parametric analysis are presented in Table. 2.

Table 2- Values used for material properties in the parametric study
(Bold values represent the base values)

Value / Parameter	**1**	**2**	**3**	**4**	**5**
Modulus of elasticity along bedjoints (MPa)	8000	**12000**	16000	24000	40000
Modulus of elasticity Normal to bedjoints (MPa)	4000	6000	**8000**	12000	-
Shear modulus (MPa)	1600	2400	**3200**	4800	6400
Tensile strength along bedjoints (MPa)	0.5	1	**1.5**	2	-
Tensile strength Normal to bedjoints (MPa)	0.1	0.15	**0.25**	0.35	0.45
Compressive strength along bedjoints (MPa)	2.0	**4.0**	6.0	8.0	-
Compressive strength Normal to bedjoints (MPa)	4.0	**6.0**	8.0	10.0	-

The effects of elastic material properties

In this section the influence of elastic material properties on the interaction of in-plane and out of plane loads in unreinforced masonry walls are investigated. The elastic parameters are moduli of elasticity of masonry in x (along bedjoints) and y (normal to bedjoints) directions (E_x and E_y) and shear modulus of masonry (G).

The effects of modulus of elasticity in x direction (E_x)

As shown in Table. 2, interaction curves for 6 different values of E_x are obtained. The curves are presented in Fig. 6. The interaction curves show that the interaction between in-plane and out of plane loads decreases by increasing of parameter E_x. Results show that the curves approach a unique curve with increase of the modulus of elasticity.

The effects of modulus of elasticity in y direction (E_y)

Interaction curves for 4 different values of $E_y$are also obtained. The curves are presented in Fig. 6. Results show that the interaction between in-plane and out of plane loads, increases by increase of E_y.The results of these two parts and comparison of obtained curves, show that interaction would be more critical in walls constructed with more brittle materials. Also the influence of the modulus of elasticity along bedjoints is more than the effect of the modulus of elasticity along the other direction.

The effects of shear modulus

Interaction curves for 5 different values of Gare obtained. The curves are presented in Fig. 6. The interaction decreases by increase of shear modulus. Unlike the parameters $E_x$and E_y, increase of the parameter G, decreases the interaction in masonry walls in most cases.

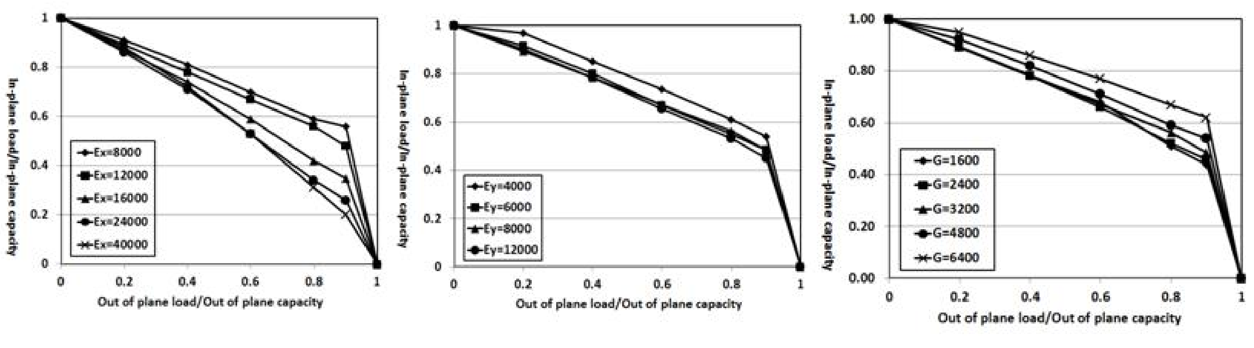

Figure 6. The effects of modulus of elastic material properties on the capacity interaction curves of walls

The effects of masonry tensile strength

Similar to the last section, to investigate the influence of tensile strengths in both directions all other parameters are kept constant and only the considered parameter is variable. In this section the results of the parametric study are presented.

The effects of tensile strength of masonry along x direction (F_{tx})

Interaction curves for 4 different values of $F_{tx}$are obtained. The curves are presented in Fig. 7. Here, because of convergence problems, the fracture energy is taken dependent to the tensile strength linearly and changes simultaneously with tensile strength. Comparison of the curves shows that in-plane and out of plane loads interaction decreases by increasing of the tensile strength of masonry along bedjoints.

The effects of tensile strength of masonry along y direction (F_{ty})

To investigate the sensitivity of the interaction curves to the parameters F_{ty}, a procedure similar to the last section for tensile strength along x direction is applied. Similar to the last case the fracture energy is assumed varies linearly with tensile strength. Interaction curves for 4 different values of $F_{ty}$are obtained. The curves are presented in Fig. 7. Comparison of the curves shows that interaction decreases by increase of F_{ty}.

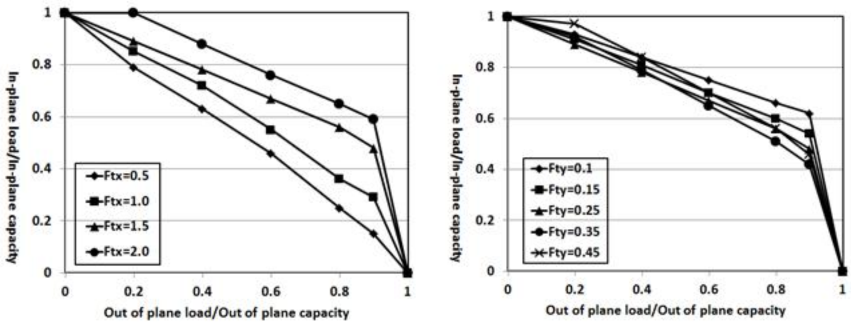

Figure 7. The effects of masonrytensile strength on the capacity interaction curves of walls

The effects of masonry compressive strength

Similar to the last sections, to investigate the influence of masonry compressive strength in both directions, all of the other parameters are kept constant and only the considered parameter is variable. In this section the results of the parametric study are presented.

The effects of compressive strength of masonry along x direction (F_{cx})

Interaction curves for 4 different values of $F_{cx}$are obtained. The curves are presented in Fig. 8. Similar to the tension domain section, because of convergence problems, the respective fracture energy is taken dependent linearly to the compressive strength and changes simultaneously with it. Comparison of the curves shows that in-plane and out of plane loads interaction increases by increasing of the compressive strength of masonry along bedjoints. Also, the curves approach a constant curve by increasing of F_{cx}.

The effects of compressive strength of masonry along y direction (F_{cy})

To investigate the sensitivity of the interaction curves to the compressive strength normal to bed joints(F_{cy}) procedure similar to the last sections for the x direction is followed. So compressive strength and corresponding fracture energy are considered variable and the interaction curves are derived.Interaction curves for 4 different values of $F_{cy}$are obtained. The curves are presented in Fig. 8. Comparison of the curves shows that interaction increases with increase of the compressive strength normal to bedjoints, but the increase rate is not similar and uniform.

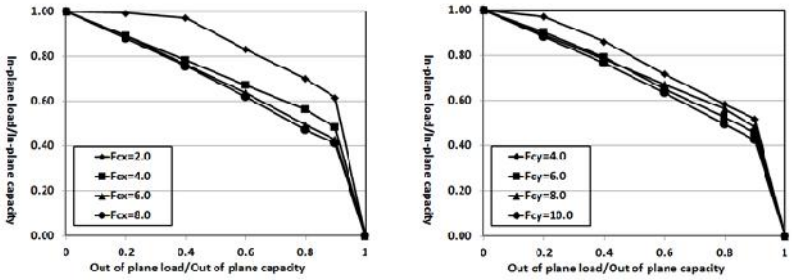

Figure 8. The effects of masonrycompressive strength on the capacity interaction curves of walls

CONCLUSIONS

A program of numerical investigations aimed at evaluating the effects of different geometric and material properties on the in-plane and out-of-plane capacity interaction in brick walls was reported. At first stage, a numerical macro model in software Diana which can simulate the interaction of in-plane and out of plane loads in masonry panels was developed and verified by previous test results. Then the parametric study was performed.It is found that the wall’s aspect ratio, the elastic material properties and the inelastic material properties in tension have the most influence on the level of interaction and the shape of the interaction curve.

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