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Finite Element and Equivalent Frame Analysis of Masonry Façade; Having an Arched Opening

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ABSTRACT: This paper aims at contributing towards the seismic response of unreinforced masonry building having an arched geometry through the use of non-linear and linear analysis approaches. The finite element method has been used to analyze the masonry structure to locate the principal stress concentration at the target displacement and the equivalent frame method (EFM) is has been used to identify the location and type of failure generated during the seismic analysis through the developed hinges. Till date, the equivalent frame analysis was based on rectangular opening of masonry façade. The present study deals with the non-linear static pushover analysis of the experimental model. The Equivalent Frame model is proposed with an arched geometry beam element to include the arching action in the spandrel, and pushover analysis is then performed using user-friendly program code SAP2000. The result obtained from the Equivalent Frame model has been compared with the location and type of ultimate stress concentration obtained with the Finite Element model and with the damage patterns obtained from the experimental model. The demand curve obtained through EFM was compared with cyclic response of the experimental model are similar in nature.

Keywords: Arched geometry, Equivalent Frame Method, Finite Element Method, Pushover analysis, SAP2000, Un-reinforced masonry.

I. INTRODUCTION

The seismic vulnerability assessment of an existing Un-reinforced masonry (URM) structure is one of the major areas of concern for structural engineers. A enormous number of old masonry buildings, characterized by material degradation and historical value, located in the earthquake-prone zone had been damaged due to earthquakes of various intensities. These old masonry buildings, because of their cultural and historical impact in the particular regions, need to be retrofitted and strengthened work for their preservation. A proper seismic analysis work is required to identify the type and location of the stressed portion of the un-reinforced masonry building which needs to be retrofitted.

For the seismic analysis, several modeling approaches have been discovered to date in which the discrete element method and the finite element method based on proper mechanical behavior consideration, allows accurate determination of stress location and failure type. Apart from this, these methods are tedious and require extensive material testing which is not cost-efficient. Another simplified methods, the Equivalent Frame method, based on macro modeling technique was first developed by [1] and further modified in [2]. In equivalent frame analysis, the arcade system is modeled as a simplified straight beam element. The reliability of such analysis is strongly based on the approximation made to capture the arching action [3], whereas in its place the arched shaped beam is proposed using consecutive laws of [4,5] in SAP2000. The arched shaped spandrel captures the arching action, hence, enhance the analysis results.

The aim of this paper is to analyze the un-reinforced masonry façade having an arched opening using finite element and equivalent frame method and comparison of the pushover curve using two different equivalent spandrel modeling approaches. The reliability of the analysis is first checked for the 1bay 2storey building, already analyzed by other authors.

II. EQUIVALENT FRAME METHOD

The equivalent frame method is the advanced form of the POR method which assumes the storey mechanism only under which damage is only concentrated in the pier element and not in the spandrel. In the equivalent frame method, the global response of the masonry structure can be estimated with an assessment of a higher number of failure mechanisms which includes, shear failure, diagonal failure, rocking, and crushing failure (Fig. 1) with their possible location. Under this method, the pier (vertical element) and spandrel (horizontal element) are modeled as an elastic element, and their intersection as a rigid zone with possible in-elastic behavior concentrated in some definite portion of the cross-section. The effective pier height is calculated as per the (M. Dolce) criteria but there is no such formulation presented to date to calculate the effective span of the spandrel element. Generally, spandrel span length is taken as the masonry portion above the opening. This spandrel span length consideration is valid for masonry façade having rectangular or square opening but no such effective studies had been carried out till date for the seismic analysis of masonry façade having an arched opening.

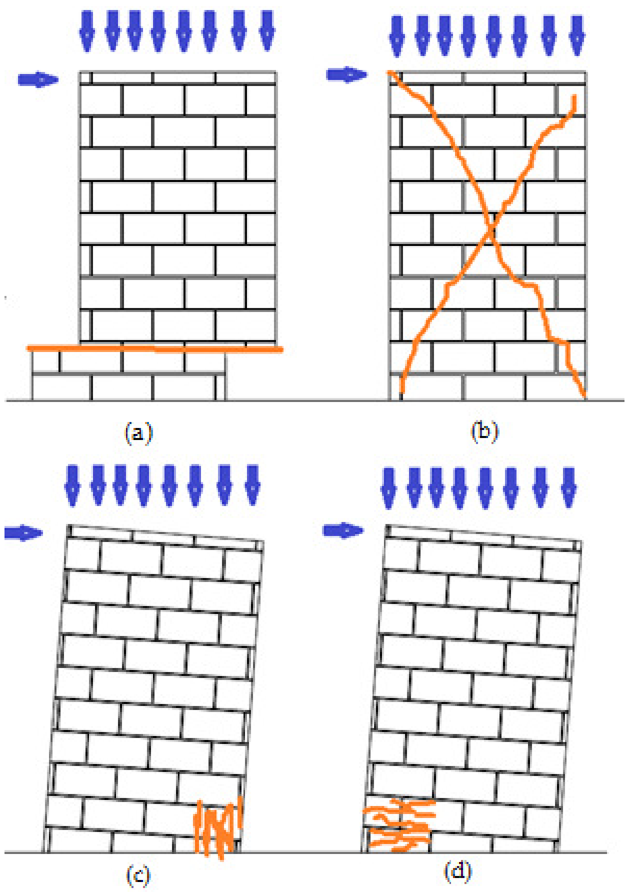

Fig. 1. Failure Pattern, (a) Sliding Shear; (b) Diagonal Failure; (c) Toe crushing; (d) Rocking Failure.

III. NON-LINEAR MODELLING

The SAP2000 [6] is an analytical tool that allows the user to capture the non-linearity of a structure by introducing the following element with lumped plasticity in an equivalent frame structure.
-Non-linear plastic hinges
-Non-linear links
The non-linear plastic hinges are used for static pushover analysis for seismic analysis of structure beyond the elasticity limit and non-linear links are used for dynamic time history analysis of the structure. The hinges with, proper strength formulation and stiffness degradation rule for structure shows approximate identical failure pattern. The adopted non-linear modeling approach of a masonry structure is described below.

-Non-linear behavior of structure for static pushover analysis.

The masonry model is assumed to be elastic-perfectly plastic and the lumped plasticity approach (Fig. 2) is used to define non-linear behavior with different failures as stated above. The standard force-displacement relation can be implemented for hinges in SAP2000 to the model non-linear behavior of the structure.

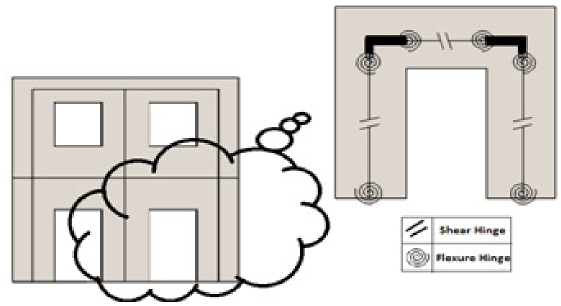

Fig. 2. EF Shear and Flexure hinge location.

Modeling of the pier, the flexure strength (Mu) for rocking or crushing may be calculated as the (1) given in [7, 8]. The shear strength criteria, based on different experimental results, it was assumed to consider two different approaches. The first criterion, (2), is referred to the diagonal cracking in existing building, was modified by [9] which was formerly advised by [10] based on experimental outcomes. The second criterion, sliding shear failure, is calculated as (3) given [7]. The second criterion is basically to evaluate the shear strength of the new building, which was differently formulated and presented [11].

$$M_u = \frac{\sigma_0 D^2 t}{2}\left(1-\frac{\sigma_0}{k f_d}\right) \tag{1}$$

$$V_u^f = \frac{\frac{3}{2} f_{v0d} D t}{\varepsilon}\left(\sqrt{\left(1+\frac{\sigma_0}{\frac{3}{2} f_{v0d}}\right)}\right) \tag{2}$$

$$V_u^s = \left(\frac{\frac{3}{2} f_{v0d}+\mu\frac{\sigma_0}{\gamma_m}}{1+\frac{3H_0}{D\sigma_0} f_{v0d}}\right) Dt \tag{3}$$

To model the spandrel, it's strength mainly depends on many factors like end restrained conditions, unit interlocking, type of lintel (whether timber or steel lintel or masonry arch). As stated in [4], the shear strength of spandrel having masonry arched geometry, may be estimated as equation (4) and (5), characterized as cracking through joints or units respectively, while the flexure strength of spandrel may be estimated as (6).

$$V_{p,s1} = \frac{2}{3} c_p h_{sp} t_{sp} + V_{arch} \tag{4}$$

$$V_{p,s2} = h_{sp} t_{sp} \frac{f'_{bt}}{2.3(1+\alpha_v)} + V_{arch} \tag{5}$$

$$V_{p,fl} = f_t \frac{h_{sp}^2 t_{sp}}{3 l_{sp}} + V_{arch} \tag{6}$$

The initial stiffness of the masonry element is estimated as the Timoshenko beam theory and bi-axial or stepwise strength degradation of masonry panel is consider for its yielding and ultimate failure behavior. The ultimate displacement capacity (δu) of shear plastic hinge corresponds to shear failure behavior is calculated as 0.4% of the deformable height of the masonry panel minus elastic deflection (δe), whereas ultimate deformation capacity (δu) of the plastic hinges corresponds to rocking failure is calculated as 0.8% of the total deformable height of the masonry panel minus total elastic deformation (δe) [8]. The failure of the pier occurs when the maximum of the panel rotation or deformation takes place first. The formation of either flexure or shear hinge replicates the type of failure pattern induced in the structure.

IV. VALIDATION OF MASONRY MODEL

A detailed EF model is prepared in SAP2000 as per the geometry given [12]. The mechanical properties used for the study, modulus of elasticity 1650[Mpa]; thickness of the wall 0.6[m]; volumetric mass 2[t/m3]; tensile strength 0.1[Mpa]; compressive strength 3[Mpa]; Poisson ratio 0.2, some other required properties of masonry are so adopted as per the design standards [13].
The geometry of a masonry façade and Equivalent Frame model is shown in Fig. 3. The length of end rigid off-set is estimated as the criteria proposed by M. Dolce. The mechanical action of masonry pier and spandrel is modeled as the equation given above and two flexure hinges are assigned at the two ends of the beam element with one shear hinge at mid-span Fig. 2.
The results of the analysis are summarized in Fig. 4 for 1Bay 2storey masonry façade. It is seen that the obtained results in the study give a satisfactory result concerning [12] and gives an acceptable percentage of error in estimated initial stiffness and peak base shear.

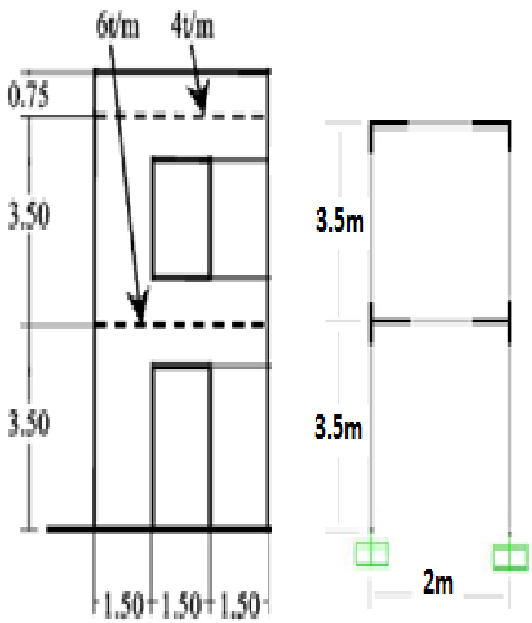

Fig. 3. 1Bay 2Storey geometry of masonry façade [12].

Table 1: Validation of present study.

	Base shear @5mm Top displacement	% error
Salonikios *et al.*	178.668	0.42%
Present study	177.911	

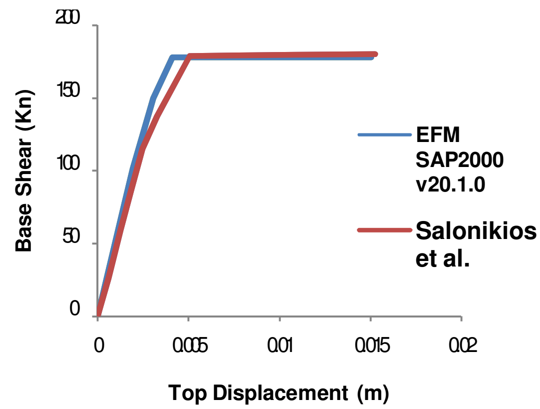

Fig. 4. 1 Bay 2 storey; pushover curve plotted between base shear and top displacement.

V. PUSHOVER ANALYSIS OF UN-REINFORCED MASONRY FAÇADE HAVING AN ARCHED OPENING

The masonry model having arched geometry was experimentally studied by [14]. He experimentally studied the response of masonry walls, having timber lintel and having an arched opening, under cyclic loading. Here, we are only concern on the non-linear static response obtained by the masonry wall with an arch opening. For this, the equivalent frame model with an curved shape spandrel element has been proposed to capture the arching action of the masonry façade. The geometry of the masonry wall is taken as Fig. 5 [14]. Furthermore, we will check the accuracy of base shear obtained with curve frame and straight frame beam element.

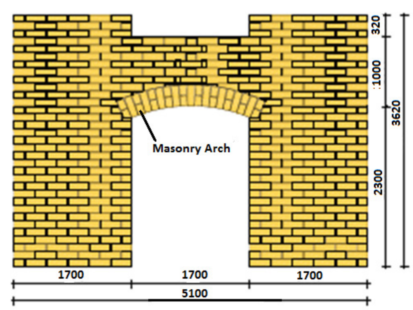

Fig. 5. Geometry of masonry wall [14].

Table 2: Mechanical properties of the material [15,16].

Masonry Material	Compressive strength (fm)	Tensile strength (ft)	Elastic modulus (Em)	Rigidity modulus (Gm)
Tuff stones	4.13 [Mpa]	0.23 [Mpa]	1540 [Mpa]	440 [Mpa]
Pozzolana Mortar	2.50 [Mpa]	1.43 [Mpa]	1520 [Mpa]	660 [Mpa]

A. Equivalent Frame and Finite Element model

The Equivalent Frame model of the masonry geometry (Fig. 5) is prepared using a user-friendly designing program SAP2000. As static pushover analysis gives the ultimate strength of structure before failure, so, for estimation of the seismic behavior of masonry façade up to the plastic limit, the nonlinear behavior of the masonry element is modeled by inserting the plastic hinges as the criteria discussed in previous section. The one or more hinges gets activated once the developed stresses exceeds the ultimate strength of the element. The equivalent frame of masonry piers is modeled as a simplified elastic beam element, whereas the spandrel element is modeled using two different approaches. First, with regular straight beam element (EFM, A1) which can usually be seen in EFM, secondly with curved frame configuration (EFM, A2) was used to model spandrel with arched geometry (

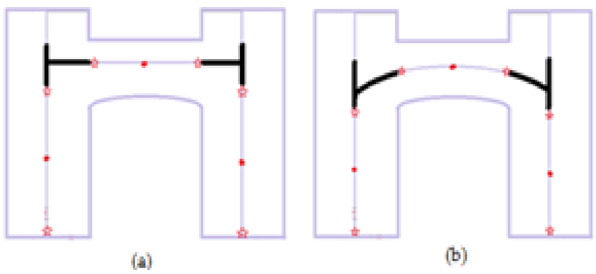

Fig**. 6** Equivalent Frame Method, Straight beam element EFM A1(a); Curved beam element EFM A2(b)

). The Dolce criterion is used to model coupling length between pier and spandrel. The insertion position for hinges in pier is the same as the [12,8] but for spandrel based on [14,17,18], there is mainly three types of governing strength i.e. flexure strength, shear strength or mixed type failure, therefore to account these failure modes two flexure hinges at the corners and one shear hinge at mid-span is provided. The mechanical strength of hinges provided in arched shape spandrel was estimated as equation 4, 5, 6 [4].

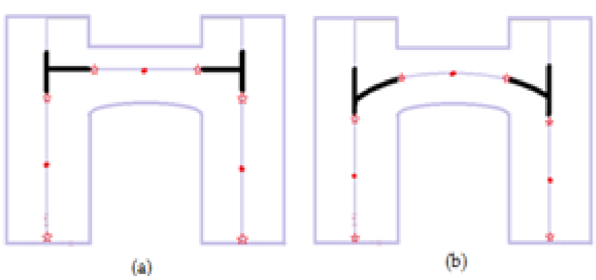

Fig. 6 Equivalent Frame Method, Straight beam element EFM A1(a); Curved beam element EFM A2(b)

For the Finite Element analysis, the structure is modeled using the four noded thin shell element in SAP2000 v20.0.1 having identical geometrical and mechanical structural properties as the experimental façade. The Equivalent Frame and Finite Element model is analyzed under a pushover load case, to a target displacement of 15mm. The result obtained after the pushover analysis of the EF model and FE model is then studied.

VI. RESULT AND DISCUSSION

The result obtained in the equivalent frame method is then compared with the stress concentration and the damage pattern of the experimental work [14]. The damage pattern of the masonry façade due to the cyclic lateral loading in the experimental work has been shown below.

Experimentally, there's no cracking was detected at the pier-spandrel intersection area. Due to the generation of excess tensile or compressive stresses at the bottom of the pier rocking or crushing failure mode respectively, gets activated on either end of the pier. Besides, the diagonal shear and flexure cracking in the spandrel panel above the opening [14] spanning between the pier element. The X-shaped diagonal failure was seen in spandrel during experimental analysis is due to the cyclic loading effect.

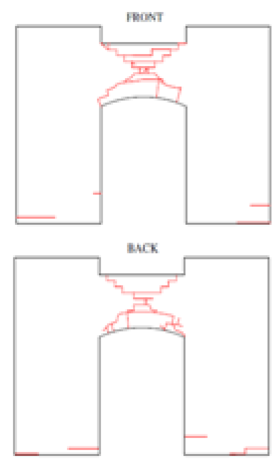

Fig. 7. Experimentally observed crack pattern.

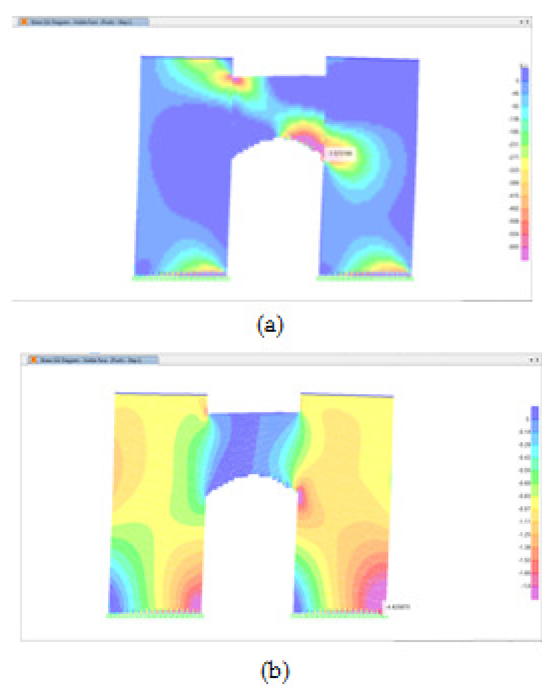

Fig. 8. Principal Stress Concentration; (a)Tensile stress

, (b) Compressive stress.

The Finite Element analysis result shows that the maximum principal tensile stress (Fig. 8a) concentration most likely to occur at the opening of masonry. It is clear from the above figure that the average value of principal stress is about 1.57 [MPa] (about 3.22 mm top displacement), which exceeds the maximum value of 1.29 [MPa] theoretical stress [15,16]. The exceedance of generated principal tensile strength concerning the threshold value of material tensile strength, diagonal tensile failure gets generated around the wall opening as stated in [19]. (Fig. 8b) shows the compressive stress generated due to the pushover load case. The maximum stress concentration can be seen at the ends of the pier element of 4.42 [MPa] is generated which exceeds the allowable stress of 3.96 [MPa] [15,16] which results in toe crushing of the pier element [20].

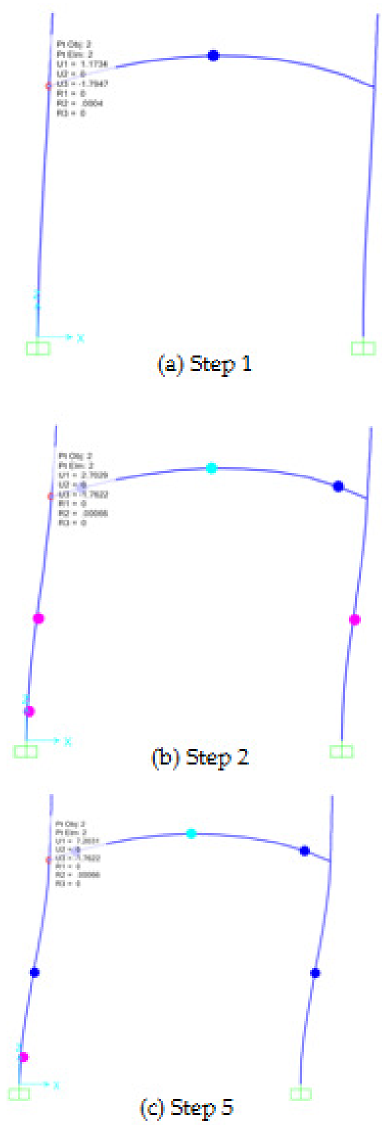

Fig. 9. Deformed structure of EFM (EFM, A2) model for pushover load case.

As we compare EFM with FEM results, we can conclude that in both the analysis diagonal shear and vertical flexural failure crack (Fig. 8a and Fig. 9a) can be seen in spandrel first, at the 1st step of 1.17 mm of lateral top displacement and later on the horizontal flexure crack were observed (Fig. 8b**Error! Reference source not found.** and Fig. 9b) at the base of the pier. Here, Fig. 10 shows the comparative plot between the base shear and top displacement obtained from the experimental program and the Equivalent Frame Method (Pushover analysis) with different spandrel modeling approach (EFM, A1; EFM, A2). The model EFM A1 shows lesser peak base shear concerning the EFM A2 model, this is because the fact that arched beam shows an arching action which increases the resisting capacity as compared to the straight beam element.

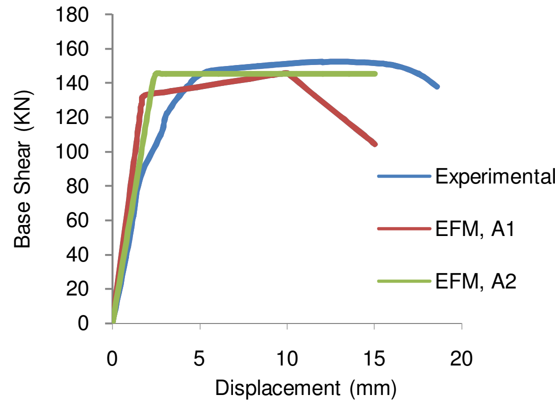

Fig. 10. Base shear v/s Top displacement for different analysis approaches

VII. CONCLUSION

The study has revealed that the Finite Element Analysis gives a better approximation of generated principal stresses. Also due to stress concentration diagonal failure usually occurs at the corner openings. Further, there is good correlation of the developed hinges with the observed damage pattern of the masonry wall with an arched opening. On comparing the demand curve obtained from the curved beam element a good correlation was observed with an experimental curve. The proposed system improve the ability of the method of capturing the response of arcade system and decrease the computational efforts. It was also concluded that the equivalent frame method can also be used for pushover analysis of masonry façade having an arched opening.

VIII. FUTURE SCOPE

This study can further extends with 3-dimentional model to capture the global response of the masonry structure. Further research work should requires to capture the variation in axial stresses during the seismic loading.

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Conflict of Interest: There is no such conflict of interest

associated with the study.

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