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Homogenization of Masonry Wall using Sensitivity Analysis

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Abstract*— Though masonry buildings are most impacted during earthquakes, and the construction of masonry structure cannot be completely avoided in all part of the earth, there is no proper study regarding the behavior of masonry structure regarding seismic performance analysis and design. Detailed analysis of masonry structures requires a detailed micro-modeling technique using finite element method which requires complex calculation and numerous parameters for analysis. In this paper, an approximated simplified finite element computational technique for non-linear analysis of masonry wall is proposed using sensitivity analysis for the flow parameter of masonry wall using a macro-modeling approach in which the masonry unit and mortar are homogenized into a single panel. An experimental wall in which the nonlinear analysis was performed was considered and numerical simulation using a macro-modeling approach is performed with the experimental properties in ABAQUS Software. With making numerical model, tensile and compressive stress-strain curve were obtained which were used to prepare concrete damage plasticity model for the modelling of masonry wall. The sensitivity analysis was performed for the determination of viscosity parameter and dilation angle. The model is prepared and run with various changing values of viscosity parameter and the one that matches with the experimental result was selected. In the same way, the model is prepared for various changing values of dilation angle and the one that matches with the experimental result was selected. The final model was prepared with the values of dilation angle and viscosity parameters thus prepared and the nonlinear force displacement relation was obtained. Thus obtained, non-linear force displacement curve is compared with the actual experimental force-displacement curve.

Index Terms—**Finite Element Method, Macro-Modeling, Masonry, Model Homogenization, Sensitivity Analysis.**

I. INTRODUCTION

Masonry structures are one of mankind's oldest building technologies, with the first use about six hundred years ago supposed to have been. Masonry remains an integral part of today's built environment and continues to be used in numerous regions worldwide. It has become the most widely-used construction form both in the poor and developing countries, because of the low cost and esthetic value associated with masonry structures. The largest buildings and monuments for historical purposes are mostly masonry and should be maintained for future generations as they bear special and/or unique witness to previous cultures. Before rational engineering design procedures were developed, most of these buildings were built, and therefore rational approaches to evaluation are needed which are well supported and validated by experimental research [1].

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The high seismic vulnerability of all masonry structures under seismic stress is a common feature. Since the fragile and anisotropical structures are masonry and each one is then characterized by a different, fragile and anisotropic behavior.

The harm caused by masonry takes place as local cracks. The distribution of these breaks in the structure determines the creation of a failure mechanism and thus the potential of the structure under loading conditions. The creation of traditional and advanced research methods for structural analysis of masonry buildings was taken into account for this structural behavior [3]. In the light of this evidence, further testing, development and improved protection against seismic demands are clearly needed to improve masonry's structural behavior [4].

The overall maceration response depends on the mechanical features and component relationship (block and mortar). Masonry components typically have an almost fragile response to voltage and compression. Compressive behaviour is particularly characterized by a much higher strength and fracture energy values compared to tensile behaviour. Besides the non-linearity of the macerating elements there is usually a very weak relationship between blocks and mortar, which is characterized by a coherent frictional shear (with basically irrelevant cohesion for dry-stone macerating) that is usually stress based and often includes softening the cohesion. The total reaction of the masonry is therefore extremely nonlinear. Modeling techniques for structures in masonry are divided into four major categories: models on block, models on continuum, macro-element modeless, and geometric model [5]. It is also critical that the numerical model captures the failure mechanisms that can take place in stemming processes.

An approximation of a macro-modeling process with ABAQUS Software for the non-linear analysis of the masonry structure is proposed in this paper by means of a sensitivity analysis in which masonry and mortar property are homogenized into one unit. Because of the reduced time and storage conditions and user friendly Mesh Generation, macro modelling is more realistic. This modeling type is most precious if there is a need for a balance between precision and efficiency [7]. Specific damage Plasticity model is used for wall modelling and the overall flow law as a plasticity model.

II. SENSITIVITY ANALYSIS

In structural optimization and design, sensitivity analysis plays an important role [8] [9]. The extent of the variance on the input parameters and to calibration & validation of mathematical models is necessary to decide how the model output is changed [10]. Computer models are used intensively

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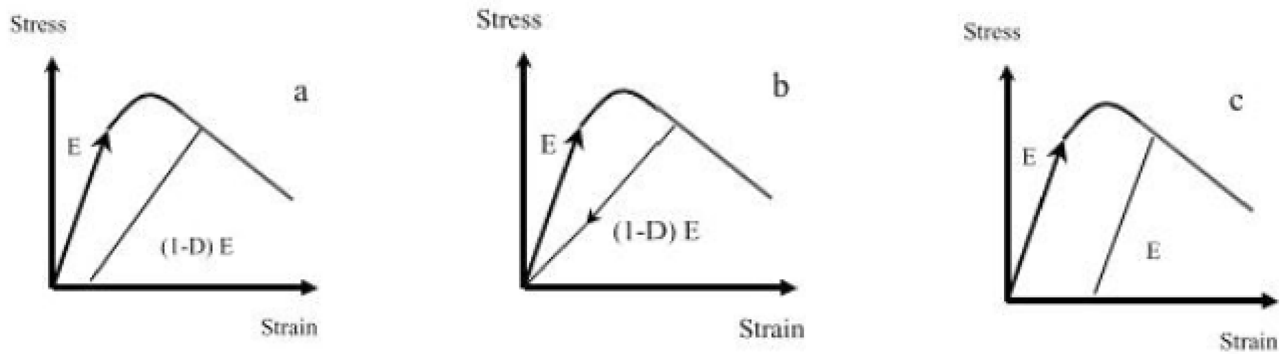
to evaluate or to forecast future results in engineering. In this regard ambiguity and study of sensitivity are of great help [11]. An analysis of current literature indicates a certain degree to improve computational efficiency and accuracy [11] through the use of an analytical tool for the measurement of sensitivity.

III. CONCRETE DAMAGE PLASTICITY

Concrete constitutive activity with elastic damage models or plastic laws is very difficult to catch. Irreversible strains cannot be captured in elastic harm models. Fig. 1(b) shows the stress of zero to be the same as a stress of zero which overestimates the damage value. On the other hand, if an elastic plastic relationship is established the strain is overestimated, because the drainage curve follows the elastic paste as shown in fig. 1 (c). The Plasticity (CDP) model which combines these two approaches can capture the experimental unloading compound, as illustrated in Fig. 1(a)[13].

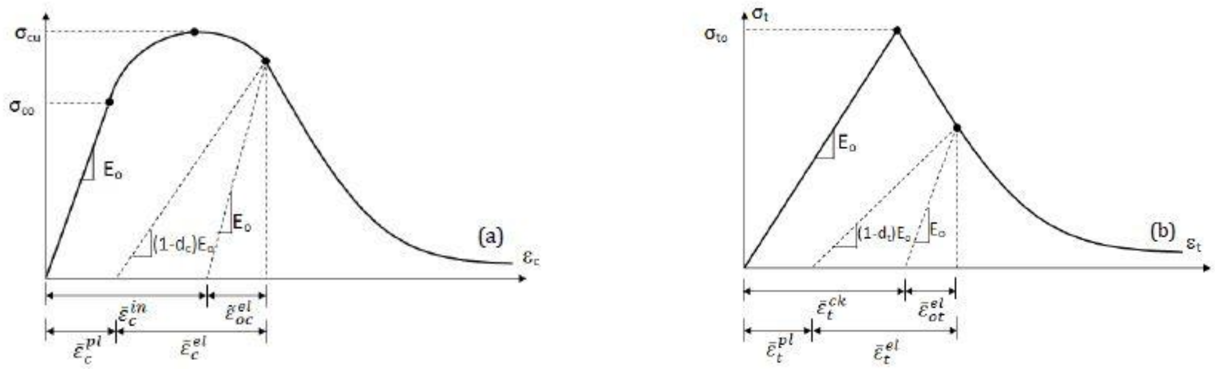


a) Experimental **b) Damage Model** **c) Plastic Model**

Fig. 1. Loading-Unloading Behavior, Experimental and Simulated Behavior [13]

The plasticity model for concrete harm offers the general ability to model concrete and other near-breakable materials, including masonry. In combination with isotropic tensility and compressive plasticity, it represents inelastic concrete action using the principle of isotropic damaged elasticity. The failure is primarily driven by train cracking and compressive delivery in the case of concrete damage plasticity. Tensile and compressive stress stretch curves and degradation factors are required for these parameters. The remaining inelastic parameters which determine the flow rule are the ratio of second pressure invariant to the tensile meridian (K), The equinoxic initial production stress ratio for the regularization of concrete constituent model to initial uniaxial stress for compression yields (fb0/fc0), the p-q plane dilation angle, the flow potential eccentricities (e). The default value e, K, and fb0/fc0 are respectively 0.1, 2/3, and 1.16 [14].

CDP can be defined as shown in Fig. 2 as tensile and compressive Concrete or masonry element models:



a) Compressive Stress-Strain Representation **b) Tensile Stress-Strain Representation**

Fig. 2. Stress-Strain Representation of Concrete or any quasi-brittle material [14]

As shown in Fig. 2, due to its elastic rigidity the reaction of the unladed concrete specimen appears to be diminished. Two harmful variables are used to deteriorate the elastic rigidity of the stress branch and can take values from nil to nil. Zero is the harmless material representing total strength loss [14]. E0 means the original material elastic rigidity (damaged) and the compressive plastic strain, tensile strain, inelastic strain and inelastic compressive strain (~pl, ~in,) respectively are the material's original elastic rigidity. Links between stress and stress are considered under uniaxial tension and compression (1), (2).

$$\sigma t = (1-\delta t)\times E_0 \times (\varepsilon t - \varepsilon t \approx pl) \qquad (1)$$

$$\sigma c = (1-\delta c)\times E_0 \times (\varepsilon c - \varepsilon c \approx pl) \qquad (2)$$

IV. METHODOLOGY

The experimental model which was carried out by Raijmaker in 1992 and used by Lourenco [15] is used for the validation of the proposed method of homogenization. In this study, the experimental model from Raijmaker's experiment is taken along with the experimental result regarding lateral force vs displacement along with other parameters like tensile

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and compressive strength of the masonry wall. While using the Concrete Damage Plasticity model, we need to provide the in-elastic behavior of the masonry wall to wall represent the actual model through the experimental results. For this purpose, we need to determine the in-elastic parameters like Dilation Angle, viscosity coefficient, eccentricity, the ratio of equibiaxial to uniaxial compressive strength, and the parameter K. In this study, a numerical method using the macro-modeling of a masonry wall is proposed in which the wall properties need to be homogenized. For this purpose, the sensitivity analysis is performed regarding the viscosity parameter and dilation angle. The compressive stress-strain curve is obtained based on the compressive strength of the masonry wall from the experiment in the model proposed by [16]. The tensile behavior is obtained based upon the tensile strength of the mortar based upon the Wang and Hsu model [17]. First, the sensitivity analysis is performed on the basis of which the efficient and cost-effective mesh size is obtained for a numerical structure model. The inelastic parameter, the most representative experimental result for a pre-compression load of 0.3 mpa is achieved by means of the sensitivity analysis of the viscosity parameter and dilation angle which is further used on a wall with a pre-compression load of 1.21 mpa. If the sensitive analyses parameters validate the result for a 1, 21 MPa pre-compression load, the parameter can be considered using the macro-modeling technology for further analysis of the masonry wall.

V. EXPERIMENTAL MODEL

To validate the model, Rainmakers conducted experiments on solid walls [15]. A wide/high pier (990 x 100 mm), containing 16 unrest rain layers and 10 mm thick moors, was tested for solid clay bricks (dimensions 204 x 98 mm x 50 mm). This test was performed on a jetty (1:2:9, cement: lime: sand by volume). Before the horizontal load was monotonously increased in the top shift control, the piers had a vertical P pre-compressor power.

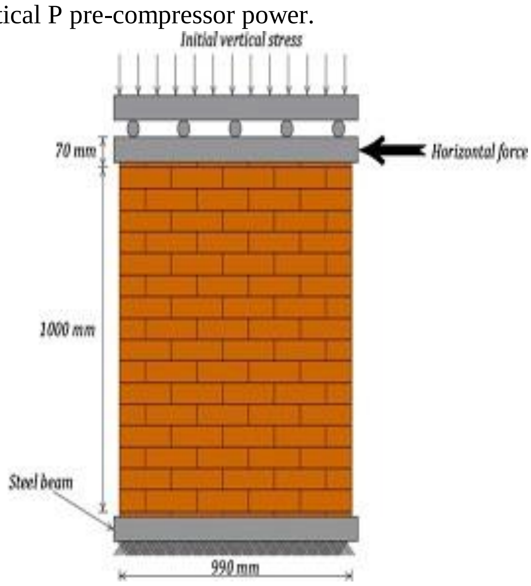

Fig. 3. Experimental Wall used for Validation of Proposed Method [15]

Table 1. The Constituent Material Elastic Properties [15]

SN	Elastic Properties	Masonry Constitutive	Solid Wall J4D and J5D
1	Elasticity	Brick (E_u) (MPa)	16700
		Mortar (E_m) (MPa)	780
		Expanded Unit (MPa)	4050
2	Poisson's ratio	Brick/Mortar	0.15

Table 2. The Nonlinear Joint Interface Material Properties [18]

SN	Non-Linear Properties		Solid Wall J4D and J5D
1	Tension	t_n^{max} (MPa)	0.25
2	Shear	c (MPa)	0.35
		μ	0.75
3	Compression	σ_c	10.5

VI. NUMERICAL MODEL DESCRIPTION

The 3D Macro Finite element numerical modeling of the masonry wall is performed in ABAQUS Software. The brick and mortar are homogenized into a single panel with the beam at the top and bottom for application of lateral as well as vertical load and for providing restrain respectively. The wall is modeled with a C3D8R element which is a eight noded brick element with one integration reduction [14]. The linear elastic properties of the masonry wall like Modulus of Elasticity, Poisson's ratio, and the unit weight of the masonry panel are applied. For the non-linear plasticity modeling, we use Concrete Damage Plasticity Model for which compressive stress-strain curve along with compressive degradation parameter and tensile stress-strain curve along with tensile degradation parameter is obtained using Kaushik, Rai, and Jain model [16] and Wang and Hsu model [17] respectively. The suitable size of the mesh is obtained by the study of the Force vs Displacement Curve for various sizes of the mesh. The variation in Force vs displacement based upon variation in viscosity coefficient and dilation angle is studied.

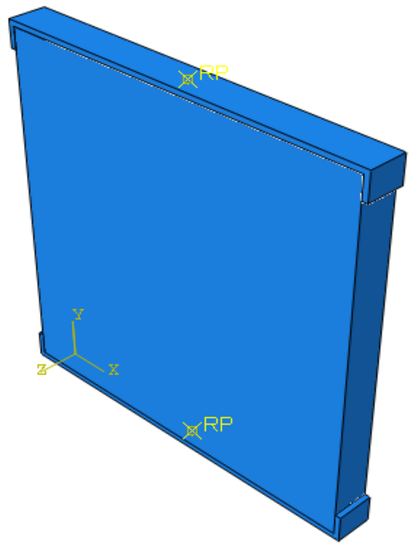

Fig. 4. Homogenized Masonry Panel with Steel Beam at Top and Bottom

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VII. RESULT AND DISCUSSION

Firstly, based upon the input value of viscosity coefficient and dilation angle and different values of mesh size, Force vs Displacement curve is obtained which is shown in Fig. 5.

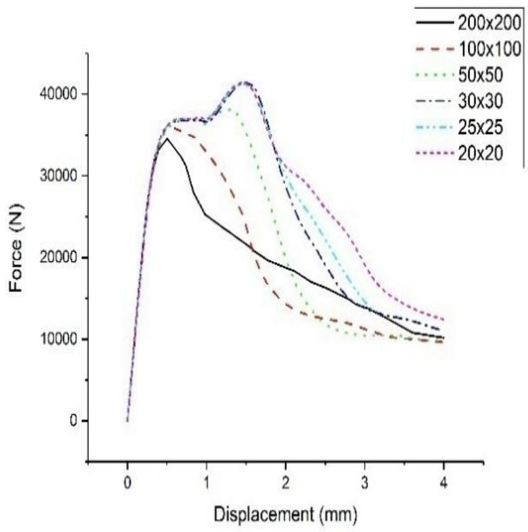

Fig. 5. Force vs Displacement Curve for Various Mesh Size for Considered Masonry Wall for a Pre-compression load of 0.3 MPa

From Fig. 5, it is seen that the result of Force-Displacement Value for a mesh size of 20 mm x 20 mm and 30 mm x 30 mm are close in value. The outcome for a meshing of 200 mm x 200 mm differs by comparatively large range with respect to meshing size of 100 mm x 100 mm. A similar large variation can be seen for a meshing size of 100 mm x 100 mm and 50 mm x 50 mm and 30 mm x 30 mm. Since, the outcome from a meshing size of 30 mm x 30 mm is closer to that of meshing size 20 mm x 20 mm, we consider a mesh size of 30 mm x 30 mm for further analysis based upon the sensitivity result.

Based upon all other variable constant with a meshing of 30 mm x 30 mm and dilation angle of 11.3°, the variation in the force-displacement relation is obtained for various viscosity coefficients as shown in Fig. 5. From Fig. 6, it is seen that with the change in the viscosity parameter, the post-yield deformation pattern of the wall is varied. For the wall with dilation angle of 11.3°, it is seen that the viscosity parameter of 0.01 and 0.05 satisfies the post-yield deformation to a greater extent. So, in Fig. 5 and Fig. 6, sensitivity analysis of the dilation angle is performed for a constant value of viscosity parameter i.e., 0.01 and 0.05.

From Fig. 7 and Fig. 8, it is seen that the experimental result is satisfied to a greater extend with a viscosity parameter of 0.01 and dilation angle 51° and next with a viscosity parameter of 0.05 and dilation angle of 11°. However, the latter is closer to the experimental result i.e., dilation angle of 11° with a viscosity parameter of 0.01. Now, these parameters obtained from sensitivity analysis are used for the analysis of the wall with a pre-compression load of 1.21 MPa and are compared with the experimental result in Fig. 9.

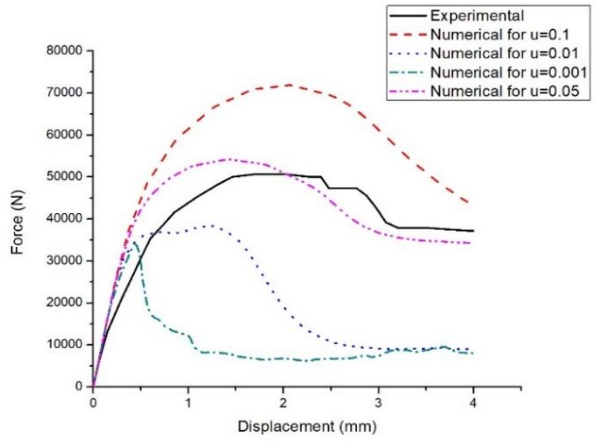

Fig. 6. Sensitivity Analysis with variation of viscosity parameter for Force displacement relation

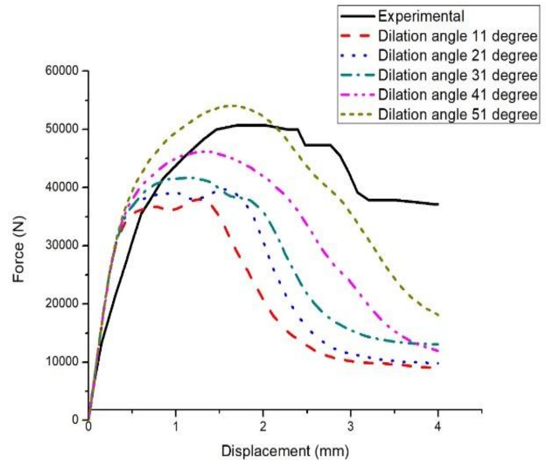

Fig. 7. Sensitivity Analysis with the variation of dilation angle for Viscosity Coefficient of 0.01

From Fig. 9, it is seen that the proposed numerical model with the modeling parameters having a viscosity coefficient value of 0.05 and dilation angle of 11 degrees along with other elastic and inelastic parameter as described in Table 1 Table 2 represents the experimental model up to the pre-yield point with higher precision and it represent satisfactorily even for post-yield deformation. So, we can use the selected parameter for further study of the masonry wall.

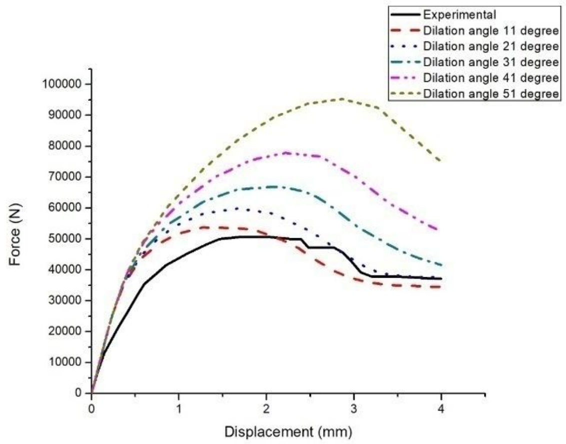

Fig. 8. Sensitivity Analysis with the variation of dilation angle for Viscosity Coefficient of 0.05

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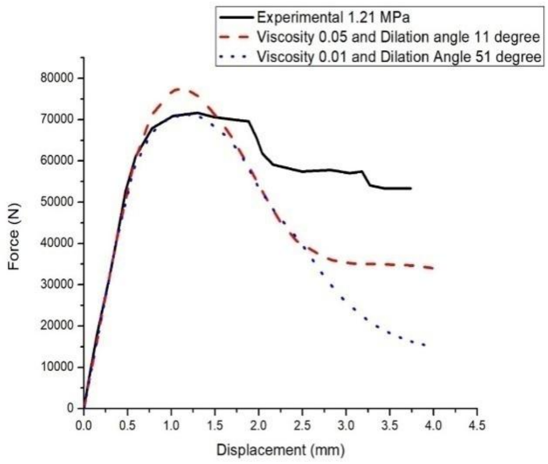

Fig. 9. Force Displacement Curve for Selected Parameters from Sensitivity Analysis for a Pre-Compression Load of 1.21 MPa

VIII. CONCLUSION

In this paper, the technique for the homogenization of material properties of a masonry wall is studied using sensitivity analysis. The major point that we obtain through this study are:

1) With the increase of dilation angle, material hardening property increases, and variation of dilation angle property causes variation in the Force vs Displacement curve.
2) The in-plane capacity of the masonry wall is sensitive to the viscosity parameter i.e., it increases with the increase in viscosity parameter.
3) The force-displacement curve for the masonry structure can be approximated based on sensitivity analysis of viscosity and dilation angle parameter. For the present study, the dilation angle is 11°and the viscosity parameter is 0.05.

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