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HOMOGENIZED MODEL FOR IN-PLANE ANALYSIS OF UNREINFORCED MASONRY WALLS

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Abstract

Masonry is an ancient construction practice used in many parts of the world. It is a low-cost construction material. Masonry wall consists of alternate layers of bricks/ blocks /stones and mortar in a particular pattern or bond. The most commonly used bond for brick masonry wall is English bond. The behavior of masonry wall is not yet properly understood due to its heterogeneous behavior. During an earthquake, masonry walls show primarily two types of failure modes, the first one is in-plane failure mode and the second one is out-of-plane failure mode. If the masonry structures are constructed properly as per codal provisions by providing various earthquake resistant elements which, will induce box action in masonry structure. Box action helps to prevent the out-of-plane failure modes of masonry walls and all the damages in wall will primarily occur in the in-plane direction. To understand the in-plane behavior of masonry walls, several experimental works have been carried out in the past which indicate that masonry walls have mostly four types of failure modes namely, (1) rocking failure, (2) toe-crushing failure, (3) sliding shear failure, and (4) diagonal tension failure. Some other mixed type of failure modes have also been reported in literature. Different types of modeling strategies have been developed for the in-plane analysis of masonry walls. It can be broadly classified into two types, (1) macro models, and (2) micro models. In macro modeling, masonry wall is modeled as a frame element with hinge assigned at the end and center of the frame to get all the failure modes of masonry wall. In micro modeling, brick, mortar and their interface are modeled individually which becomes computationally very expensive. So macro models are used when the overall behavior of masonry structures are important while micro models are generally used for the research work to understand the in depth behavior of masonry wall. Another modeling technique is, homogenized model, which is a suitable way out between the macro and micro models. In this method, the entire masonry wall is modeled as a continuum element which represents the equivalent behavior of brick and mortar. Homogenized models are useful because of its low computational time, simplicity in modeling and higher accuracy as compared to macro models.

In the present study, concrete damage plasticity (CDP) model is used for in-plane analysis of masonry wall. It is a homogenized model and also available in some of the commercial finite element software. Masonry walls are modeled using CDP model to assess the four preliminary in-plane failure modes of masonry wall and the results presented herein from the finite element simulations, which have also been compared with past experimental results. The accuracy of CDP model in the prediction of different in-plane failure modes of unreinforced masonry walls is highlighted in the current work.

Keywords: URM; in-plane; concrete damage plasticity; finite element

1. Introduction

Masonry is an oldest construction practice for the building of houses, monuments, dams, bridges etc. The masonry structures are anisotropic in nature which indicates that they have different behavior when tested about different bending axis. The source of loading may be wind, earthquake or any other natural or man-made forces. To safeguard the masonry structures against the different type of loads, it is first required to develop a suitable finite element model that can capture its actual behavior. Till date, few homogenous and anisotropic finite element models have been developed for the analysis of masonry walls. These models are basically of two types, (1) macro model and (2) micro model. In macro modeling method, entire masonry structure has been divided into different segments consisting of piers and spandrels and after that each segment is modeled using frame element ([1], [2], [3], [4], [5] and [6]). To capture the failure of piers or spandrels, hinges are assigned at the end or at the center as shown in the Fig.1 (a). The hinges can capture the compression, tension and shear failure mode of masonry wall. This method is very helpful for designers as it requires low computational time and its simplicity in design. Another modeling approach is micro modeling, which has been used to understand the behavior of masonry structure at micro level which can't be assessed using macro modeling technique. These advantages come with the cost of very high computational time because in micro modeling, brick or mortar or both brick and mortar are modeled using non-linear plasticity damage model and the interface between them is assigned using interface elements ([7], [8], [9]) as shown below in the Fig.1 (b). Micro models are very useful for research work. Another modeling approach is homogenized model, which is in-between of macro model and micro model. In this approach, masonry walls are modeled using two dimensional or three dimensional continuum element (Fig.1 (c)) and the material properties of this model are tuned in such a way that it represents the actual behavior of masonry wall as close as possible. This model can be either homogeneous or anisotropic. In the present study only homogenous isotropic model has been used to investigate its accuracy for different in-plane failure modes of masonry walls.

During an earthquake, masonry wall fails either in in-plane direction under in-plane action of loads or in out-of-plane direction under out-of-plane action of loads ([3], [6]). Both failure mechanisms are very different from each other. In the present study, only in-plane failure modes of masonry walls are considered. The preliminary failure modes of masonry wall under in-plane action of load are rocking failure, toe-crushing failure, sliding shear failure and diagonal tension failure. In rocking failure, masonry wall fails by overturning of wall about its toe. While in toe-crushing failure, it fails by compression failure of toe during the rocking action. In sliding shear failure, masonry wall fails by sliding between brick and mortar and in diagonal tension failure, it fails by tensile cracks developed along the wall diagonal ([3], [6]).

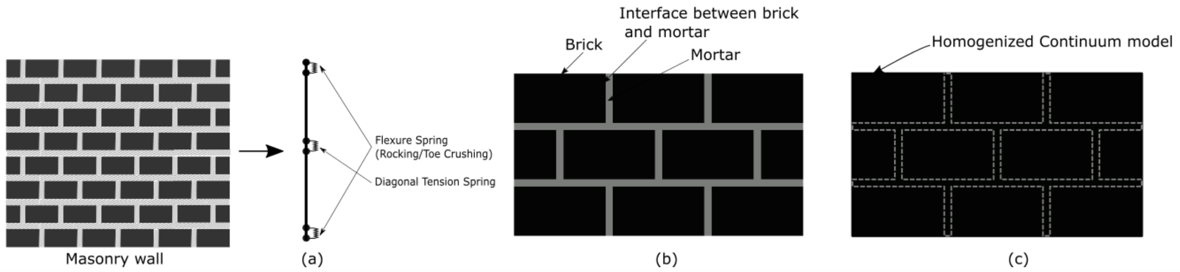


Fig. 1 - Various modeling strategies (a) Macro model (b) Micro model (c) Homogenized model

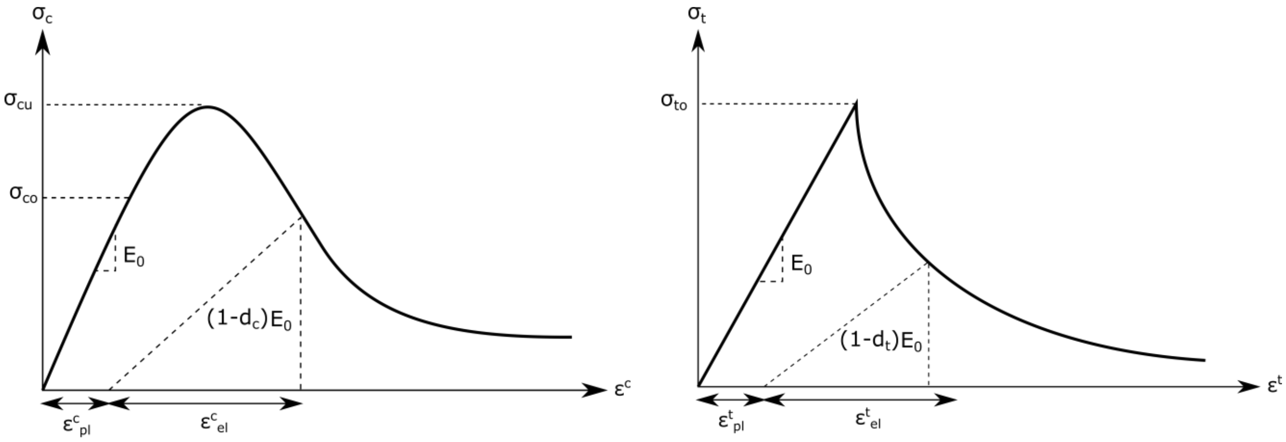
The present study focuses only on the popular concrete damage plasticity (CDP) model which is homogenized model and it follows constitutive law based on isotropic damage assumption ([10] and [11]). It was basically developed for quasi-brittle material like concrete but masonry and concrete have similar behavior in compression as well as in tension, owing to which, it has been used for the analysis of masonry walls ([12]).

In the study, dimensions as well as properties of masonry walls are taken from the past experimental work ([13], [14], [15]). The models are selected in such a way that they represent the different in-plane failure modes of masonry walls i.e., rocking or toe crushing failure, sliding shear failure and diagonal tension failure. The experimental results from these studies have been compared with analytical results obtained from the CDP model adopted in the current study. CDP model is accessible from a commercial finite element software ([10]). The results are compared here in the form of pushover curve and damage pattern.

2. Methodology

CDP model was developed for quasi brittle material such as concrete. However, experimental results suggest that masonry also behaves like concrete ([12]). So this model has been selected herein to study the different in-plane failure mechanisms of masonry walls. This is a homogeneous isotropic model and it works based on isotropic damage assumption. The detail about damage assumptions are discussed later in this section.

The CDP model requires uniaxial compression and tension stress-strain curve for the analysis in the form as represented in Fig.2 (a, b).



(a) (b)

Fig. 2 – (a) Compression and (b) Tension stress-strain curve for the plasticity modeling

In Fig.2, σ_{cu} represents the peak compressive stress, σ_{co} represents the compressive stress upto elastic limit, σ_{to} represents the maximum tensile stress at the end of elastic stage, E_0 is the elastic Young's modulus which is same in compression as well as in tension and $\varepsilon^c{}_{pl}$ and $\varepsilon^t{}_{pl}$ are plastic strain in compression and tension respectively.

The stress-strain relationships in compression and tension can be written as:

$$\sigma_c = (1-d_c)\, E_0\, (\varepsilon_c - \varepsilon^c{}_{pl}) \qquad (1)$$

$$\sigma_t = (1-d_t)\, E_0\, (\varepsilon_t - \varepsilon^t{}_{pl}) \qquad (2)$$

In Eq. (1) and Eq. (2), d_c and d_t are damage parameters in compression and tension respectively. In this study, linear damage evaluation law (to model the damage both in compression as well as in tension) is considered which indicates that damage parameter has zero value at undamaged state corresponding to σ_{cu} and σ_{to} in compression and tension stress-strain curve respectively. The damage parameters have unit value at completely damage state that is the last degrading point of stress-strain curve.

This model basically works on yield function proposed by Lubliner [11] and the flow rule given by Drucker-Prager hyperbolic function which follows non-associated flow rule assumption [10]. The yield function requires stress ratio (f_{bo}/f_{c0} = initial biaxial compressive yield stress/initial uniaxial compressive yield stress) as an input parameter which is generally taken as 1.16 for quasi brittle material and K factor which is defined as the ratio of second stress invariants of tensile meridian to that of compression meridian. While plastic potential function can be defined using dilation angle and eccentricity which is taken as 30 degree and 0.1 respectively [12].

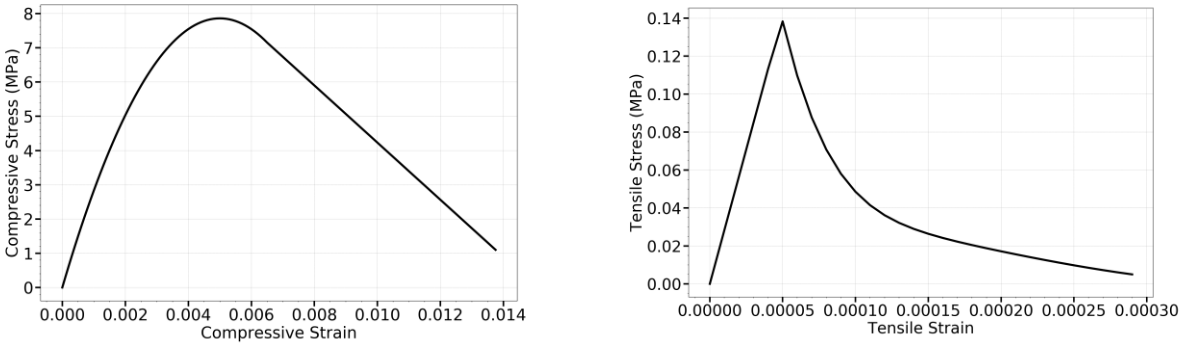
3. Results and Discussions

In this section, the accuracy of CDP model has been examined by comparing its results with experimental results for different in-plane failure mechanisms i.e. rocking/ toe crushing failure, sliding shear failure and diagonal tension failure. In all the validation study, the compression and tension uniaxial stress-strain curve required for the plasticity model have been considered using formulae available in [16] and [2] respectively.

3.1 Rocking/ toe-crushing failure

Under the action of in-plane load, entire masonry wall rotates about its compression toe and it ultimately leads to the compression failure of masonry wall near the toe region. This type of failure mode is generally observed in the masonry wall with higher aspect ratio.

To validate the plasticity model in rocking failure mode, masonry wall of size 1.5 m x 0.83 m (height x length) has been modeled using a commercial software [10]. Material properties of wall and experimental results are adopted from the research work of Franklin, Lynch and Abrams [13]. The compressive strength of wall is 7.86 MPa. The wall is subjected to vertical pre-compression of 0.29 MPa and thickness of the wall is 0.2 m. The wall is tested under cantilever boundary condition. In absence of available data, tensile strength of wall has been assumed as 0.14 MPa only because masonry has very low tensile strength ([6]). The compression and tension stress-strain curves used in CDP model are given in the Figs.3 (a) and (b) respectively. Other data required for the analysis in CDP model are given in the Table 1.



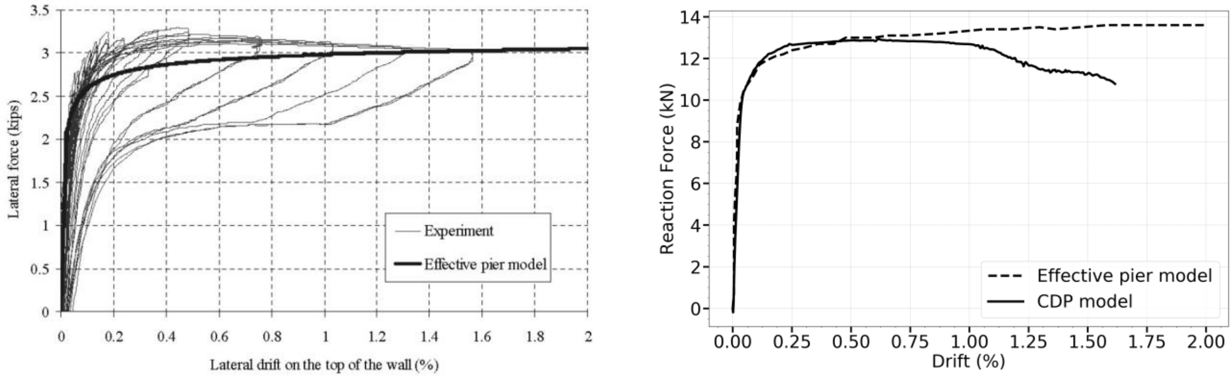
(a) (b)

Fig. 3 – (a) Compression and (b) Tension uniaxial stress-strain curves used in the plasticity model

Table 1 – Parameters required for plasticity model in rocking/toe-crushing failure mode

Material	Elastic Modulus	Poisson's ratio	Dilation angle	Eccentricity	f_{bo}/f_{co}	K
Masonry	2857.9 N/mm^2	0.19	30	0.1	1.16	0.67

The experimental and analytical ([17]) force-drift curve obtained from the past studies are plotted in Fig.4 (a) and the result obtained from finite element simulation and experiment are plotted in Fig.4 (b). Here the drift can be defined as a ratio of displacement at top of the structure to the height of the structure.



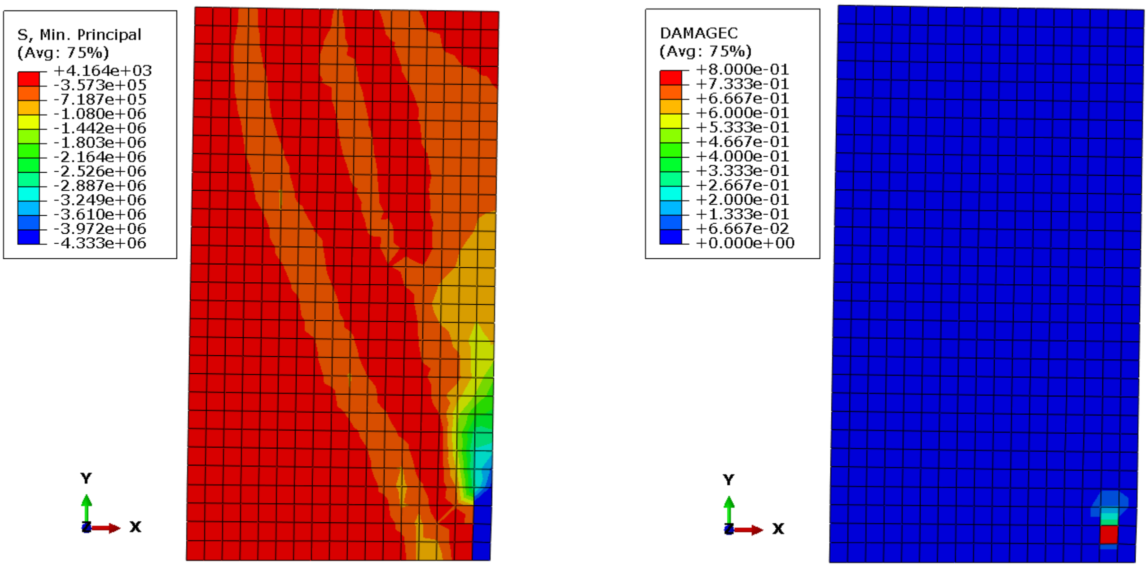
(a) Past experimental ([13]) and analytical ([17]) results (1kips = 4.448 kN)

(b) Comparison of finite element result with past analytical ([17]) results

Fig. 4 – Comparison of force-drift curve using the experimental results and analytical results

The maximum reaction force obtained from the experiment ([13]) and simulation are 15.57 kN and 12.93 kN respectively. The variation in the results in terms of reaction force is 20.4 % which is quite reasonable. Similarly, the drift capacity of the wall obtained from the experiment ([13]) and software simulation are 1.58% and 1.62% respectively. The variation in the drift prediction is 2.53%, which is acceptable.

It is seen that the result obtained by the CDP model is matching quite well with past experimental results as well as past analytical work (Fig.4 (a)) [17]. Further the minimum principal stress and compressive damage pattern obtained from the FE software simulation are plotted in Figs.5 (a) and (b) respectively. In Fig.5 (b), red part in the contour plot shows compression failure near the toe of the wall.



(a)

(b)

Fig. 5 (a) Min. principal stress and (b) Compressive damage contours obtained from the CDP model

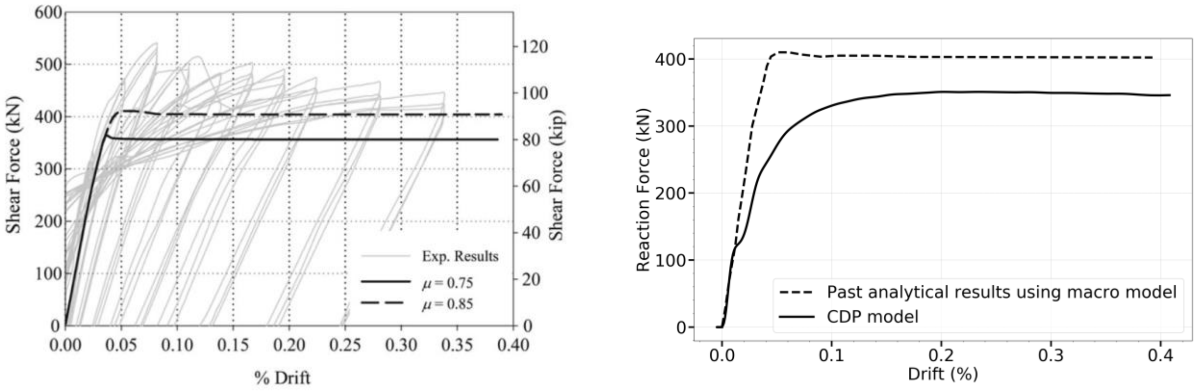
Note: +ve sign indicates tension and –ve sign indicates compression in the legends of the contour plots

During the experiment, the failure initiated by flexure tensile cracking along the bottom of the wall followed by compression failure at toe of the wall and this failure pattern was captured well in the numerical model.

3.2 Sliding shear failure

Masonry wall of size 1.96 m x 3.96 m (height x length) has been taken from [14] to study the shear failure of masonry wall. Wall is subjected to vertical pre-compression of 0.62 MPa and it was tested under cantilever boundary condition. The material properties of the wall are same as mentioned in the previous section in Table 1 and Fig.3.

The past analytical and experimental results are shown in Fig.6 (a) and the results obtained from CDP model and past analytical work are shown in the Fig.6 (b).



(a) Past experimental ([14]) and analytical results (for $\mu = 0.75$ and $\mu = 0.85$ [1])

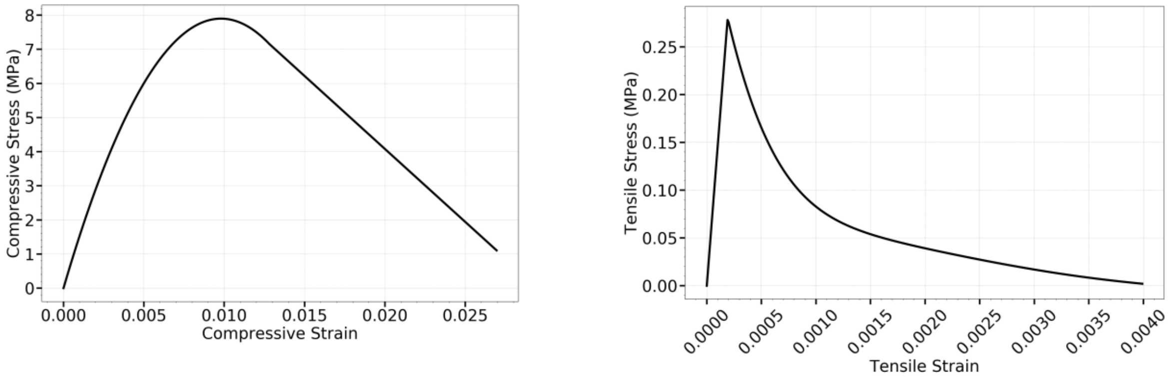
(b) Comparison of finite element result with past analytical result (for $\mu = 0.85$ [1])

Fig. 6 – Comparison of force-drift curve using the experimental and analytical results

The maximum resisting force obtained from the experiment ([14]) and analytical work using CDP model are 500 kN and 350 kN respectively. The variation in the force estimation is 42.8%. For sliding shear failure more upgradation is required in the material model. The drift capacity of the wall obtained from the experiment and CDP model are 0.34% and 0.41% respectively. The variation in the drift is 20.6% which is reasonable. It is observed that the force-drift curve obtained from CDP model is slightly on lower side compared to past experimental work.

3.3 Diagonal tension failure

Diagonal tension failure of masonry wall has been studied using the test specimen MI3 from the reference [15]. The dimensions of the wall are 3 m x 1.5 m (height x length). Thickness of the wall is 0.381 m. The wall is subjected to vertical pre-compression of 1.24 MPa. The wall has a fix-fix type boundary condition. The compressive strength of the wall is 7.9 MPa and the tensile strength of wall is 0.28 MPa. The compressive and tensile stress-strain curves used in CDP model are given in Fig.7. Other parameters required for CDP model are given in Table 2.



(a) (b)

Fig. 7 – (a) Compression and (b) Tension uniaxial stress-strain curves used in the plasticity model

Table 2 – Parameters required for plasticity model in rocking/toe-crushing failure mode

Material	Elastic Modulus	Poisson's ratio	Dilation angle	Eccentricity	f_{bo}/f_{co}	K
Masonry	1430 N/mm^2	0.19	30	0.1	1.16	0.67

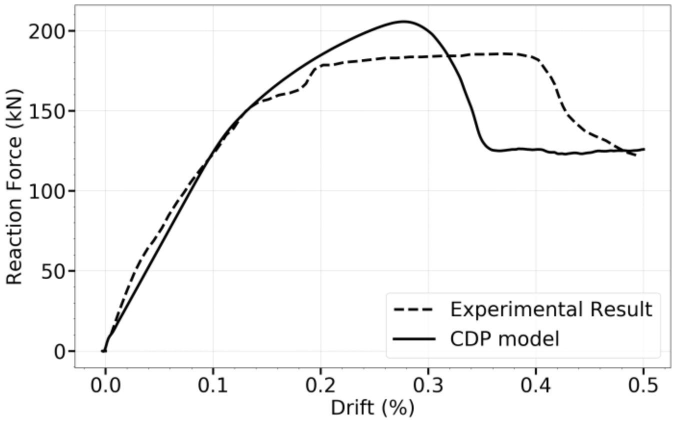
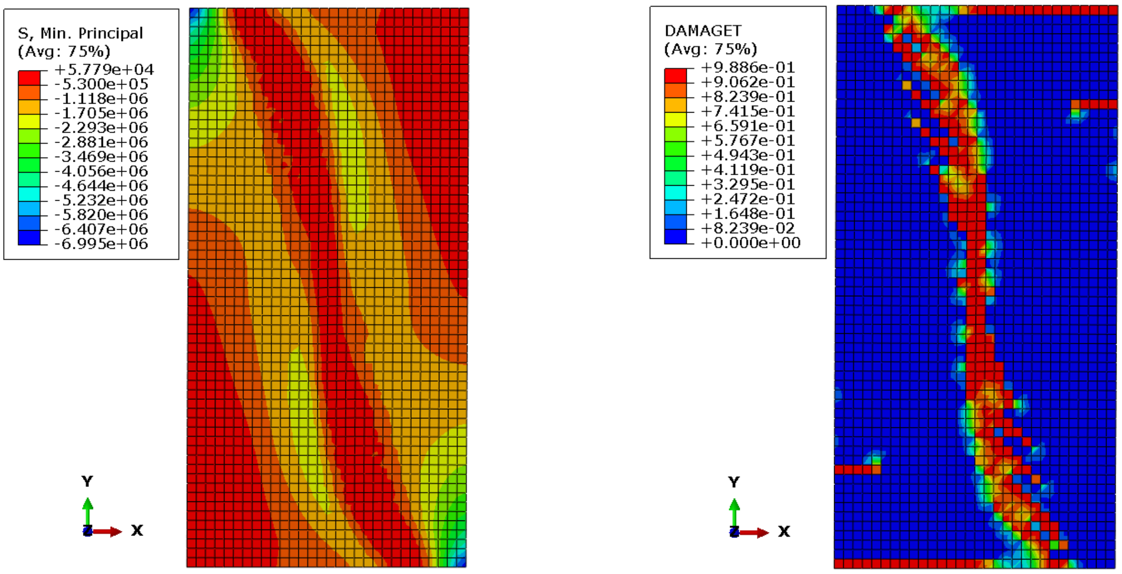


Fig. 8 – Comparison of finite element result with experimental result [15]

The experimental results and the CDP model results are compared as shown in the Fig.8 above. It is observed that the wall is failing slightly earlier in CDP model as compared to experimental result. The maximum strength obtained from the experimental result ([15]) and plasticity model are 185.6 kN and 205.7 kN respectively. The variation in the force is 10.8% which is acceptable. The drift percentage obtained by experiment and plasticity model are very close to each other (≈ 0.5%), so it has very less variation in estimation of drift capacity. Hence CDP model is effective in capturing diagonal tension failure mode of masonry wall as compared to the past analytical work using equivalent frame modeling concept ([1], [17]).

The minimum principal tensile stress and tensile damage pattern obtained by CDP model are plotted in the Fig.9 (a) and Fig.9 (b) respectively.



(a) (b)

Fig. 9 – (a) Min. principal stress and (b) Tensile damage pattern contours obtained from the CDP model

Note: +ve sign indicates tension and –ve sign indicates compression in the legends in the contour plots above

During the simulation, flexural crack was observed at top and bottom of the wall followed by diagonal tension crack starting from middle portion of the wall which represents the diagonal tensile failure of masonry wall. In Fig.9 (a), principal tensile stress has a greater value along the diagonal of the wall measured from top left corner to bottom right corner and due to this fact diagonal tension damage of the wall was observed along the same diagonal as depicted in Fig.9 (b).

4. Conclusions

Based on the foregoing studies, following conclusions are drawn.

(1) Concrete damage plasticity (CDP) model is very effective in predicting the compression (rocking/ toe-crushing) failure modes of masonry in terms of force and deformation relationship.

(2) For shear failure mode of masonry wall, the reaction force obtained by CDP model are slightly on lower side as compared to experimental results reported in literature.

(3) CDP model is very effective in capturing the diagonal tension failure of masonry wall while other equivalent frame model fails in capturing it.

(4) The damage patterns obtained in compression and diagonal tension failure modes by CDP model have a good match with experimental results.

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