NUMERICAL MODELING OF MASONRY-INFILLED REINFORCED CONCRETE FRAMES STRENGTHENED BY ENGINEERED CEMENTITIOUS COMPOSITES

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Abstract

The experiences from past earthquakes have shown the vulnerability of the most typical framed structures with masonry infills. Although current structures generally show an acceptable seismic behavior since they are designed based on modern codes, a large number of existing buildings need to be strengthened using an effective, compatible, and applicable approach. Recently, the use of high performance fiber reinforced cementitious composites (HPFRCC) as a strengthening overlay on masonry infill walls has been developed. In this paper, the numerical modeling of masonry infilled reinforced concrete (RC) frame is carried out before and after strengthening with a special kind of HPFRCCs called Engineered Cementitious Composites (ECC) using TNO DIANA software. Numerical modeling of the specimens is defined based on macro modeling approach, considering the infill panel as a homogenous material and interface elements to simulate the behavior of interface between the frame and the infill as well as the ECC layer and the infill. The results illustrate that the ECC layer increases the stiffness and strength of infilled framed in calibrated model. Furthermore, the interface elements show the various failure mechanisms of infill wall, RC frame, and ECC layer for the strengthened specimens.

Keywords: masonry infilled frames, Engineered Cementitious Composites, numerical modeling, strengthening

1. Introduction

Many reinforced concrete (RC) structures with inadequate lateral strength and ductility exhibited weak seismic performance all around the world due to various defects such as flexible columns, soft stories, weak column-strong beam connections, insufficient concrete confinement, and non-seismic reinforcement detailing [1]. Although RC structures designed based on modern codes have a good capacity to withstand under seismic loads, nonstructural elements such as masonry infills undergo a high degree of damage even for

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moderate earthquakes, causing casualties and high economic losses [2, 3]. On the other hand, infill walls can be used to strengthen RC frames. However, their potential vulnerability under in-plane and out-of-plane loading poses serious challenge in retrofitting by using infill walls. Thus, the use of existing masonry panels in a strengthening scheme for RC structures is an interesting solution, if one can avoid the failure modes of masonry panels.

A number of methods were proposed in the literature to strengthen infilled concrete frames by enhancing the in-plane shear behavior of infill panels such as using cast, in-situ or precast RC infill walls [5-6], applying reinforced plaster layers [7], and shotcreting masonry infill panels [8] to increase the stiffness and lateral strength of infilled RC frames and reduce the lateral drift at the ultimate load. Another technique proposed and tested by experimental studies (e.g. [9]) is the use of fiber reinforced polymers (FRPs). The experimental results have shown a noticeable improvement in the lateral strength and energy absorption capacity of system if adequate anchors are provided to attach FRP sheets to the masonry wall as well as to the corners of the surrounding RC frame. Recently, ECC overlay strengthening system was proposed to strengthen masonry panels and the obtained results have shown that ECC can induce an increase of about 1.5-2.8 times in the shear strength [10]. ECCs are a special class of high-performance fiber-reinforced cement-based composite materials (HPFRCCs) which are typically reinforced with short fibers and micromechanically tailored to feature high tensile ductility and multiple cracking [11].

The aim of this paper is to carry out the numerical modeling of a masonry infilled reinforced concrete frame before and after strengthening with ECC using finite element modeling by means of the TNO DIANA 9.6 software [12]. It is obvious that the numerical modeling can provide a better understanding about the exact behavior of infilled RC frame before and after applying ECC. Therefore, it is a need to introduce a numerical model and calibrate it by the experimental results.

Generally there are two approaches to simulate the behavior of the masonry wall, namely macro and micro modeling approaches. In the Macro modeling approach, infill is replaced by one or more equivalent diagonal struts [13]. The single diagonal strut method is simple and capable of representing the global behavior of infill, however it cannot predict local effects in the infill resulting from the interaction between infill and frame. In the micro modeling approach, finite element method is used to simulate the infill panel to provide insight toward understanding the local behavior of infilled frame. There are three different approaches to model the infill in micro modeling approach including detailed micro modeling, simplified micro modeling and macro modeling with considering the masonry as homogenous and isotropic material [14]. In the detailed micro modeling approach infill panel is modeled as a set of three different components: brick, mortar, and interface between mortar and brick. In the simplified micro model, infill is modelled as a set of two different elements: expanded bricks and interface elements. Interface elements represent the behavior of mortar and also the interface between mortar and brick.

In this paper, numerical modeling was defined by using macro modeling approach and considering interface elements to model the behavior of interface between the masonry infill and ECC layer. However, the infill panel was considered as a homogenous material.

2. Numerical Modeling

To carry out the objectives of this study, the adopted finite element model was calibrated based on the previous experimental results obtained from the in-plane quasi-static cyclic tests on masonry infilled RC frames [15]. The test specimens were half scale one-bay, one-story, representing the interior bay at the bottom story of the prototype frame. In the experimental program three different test specimens were considered as illustrated in Table 1. The mechanical properties of materials are represented in Table 2 and a general overview of the reinforcement details and geometry of the RC frame are shown in Figure 1.

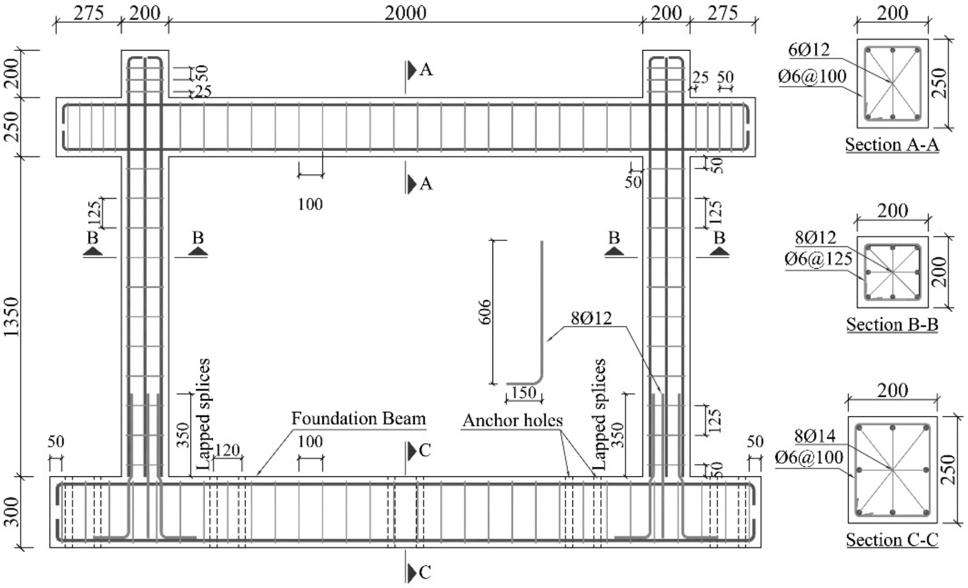


Fig. 1: Specimen dimensions and reinforcement details [15]

Tab.1: Properties of test specimens

Specimen	Type of Frame	Components
BF	Bare Frame	Concrete Reinforcement Bars
IF	Masonry Infilled Frame	Concrete Reinforcement Bars Brick
IF-DL15	Masonry Infilled Frame with ECC layers on both sides of the infill wall	Concrete Reinforcement Bars Brick 15 mm ECC Layer

Tab.2: Mechanical properties of the infilled frame’s components

Mechanical Properties	**Concrete**	**Masonry**	**Reinforcement bars**
Elastic Modulus (GPa)	32	6.05 (perpendicular to the bed joints)	210
Poisson’s ratio	0.16	0.13	-
Compressive Strength (f_c, f_m) (MPa)	BF: 35.5 IF: 40.1 IF-DL15: 35.9	11	-
Tensile Strength (f_r) * (MPa)	BF: 4.2 IF: 4.45 IF-DL15: 4.2	1.1	-
Yield Stress (MPa)	-	-	Diameter 6: 302 Diameter 12: 370.1 Diameter 14: 463.8

* calculated based on $f_r = 0.7\sqrt{f_c}$ for concrete and 10% of compressive strength for masonry

The numerical models were defined by using macro modeling approach and considering the infill panel as a homogenous material. Masonry infill and concrete frame were modelled by using four-noded shell elements. Furthermore, steel reinforcements were embedded in the concrete frame. Interface elements of (2+2) nodes were used to model the interface behavior between masonry infill and reinforced concrete frame. The mesh adopted for the RC frame is shown in Figure 2. At first, the calibration of the bare frame model was done based on the experimental lateral load-displacement curve to verify the behavior of the concrete frame and reinforcement bars. A total strain fixed-crack constitutive model was adopted for masonry and concrete material in which the tensile and compressive behavior of the materials can be directly introduced with user-defined stress-strain relationships. In addition, multi surface interface model of “combined cracking-shearing-crushing” was used to simulate fracture and frictional slip as well as crushing along the interface. A vertical load of 132 kN was applied to the top of the columns in the numerical model in accordance with what was considered in the experimental program to simulate the weight of the upper stories. Three translations and three rotations of the bottom beam and also the out-of-plane translations of the upper beam were fixed to simulate the constraints of the RC frame in a manner similar to the test procedure.

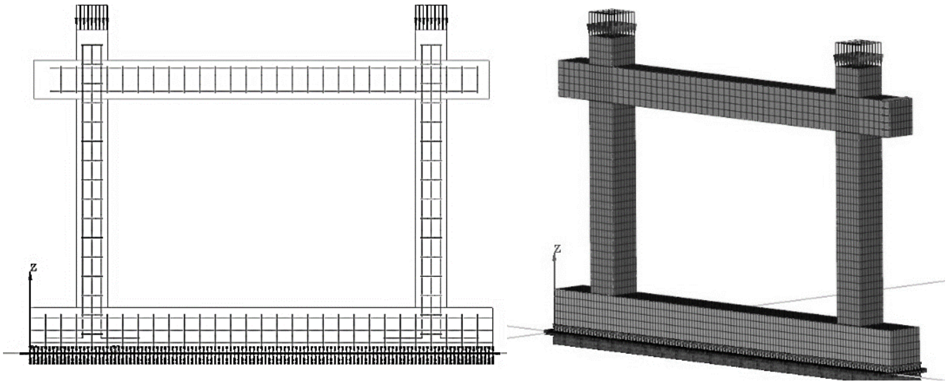
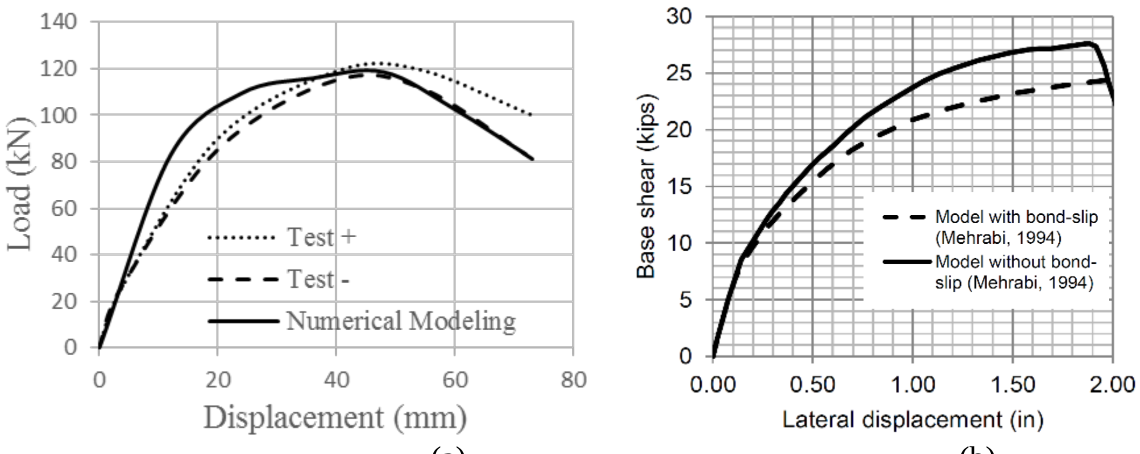


Fig. 2: The adopted mesh of the finite element model for the test specimens

3. Analysis of Results and Discussion

In the first step, the bare frame (specimen BF) was modelled, considering embedded steel reinforcements with no bond-slip effects. As shown in Figure 3-a, the lateral force-displacement curve of the calibrated numerical model for specimen BF shows a reasonable agreement with experimental results in the general trend of response as well as in the maximum strength. In this figure, “Test+” and “Test-” represent the envelop curve of tensile and compressive branch of the experimental hysteretic graph, respectively, taken from [15]. It should be noted that the lateral loading pattern developed by FEMA [16] had been selected in the experimental tests because of its step-wise increasing deformation amplitude which allows for definition of more cycles in the small and moderate drift ranges and reduction of the number of cycles in large lateral drifts. Figure 3-a indicates that the numerical model can predict accurately the initial stiffness of the experimental test. Afterwards, the model shows slightly a higher stiffness in comparison to the experimental results. This difference can be attributed to the bond-slip effect which has not been considered in the finite element model due to software limitations. Bond-slip that represents the slip between the rebar and the surrounding concrete increases the flexibility of concrete frame. Comparison between the response of a RC frame model with and without considering bond-slip has been frequently reported in the literature (e.g. [17]). Figure 3-b taken from [17] shows how considering the bond-slip effect reduces the numerical model’s stiffness. Furthermore, this study have shown that the bond-slip modeling does not affect the response of the masonry infilled frame because the ductility of infilled frame is lower than that of the bare RC frames [17].



(a) (b)

Fig. 3: (a) comparison of the numerical lateral force-displacement curve with the monotonic experimental envelop of BF specimen
and (b) Effect of modeling the bond-slip on the response of the bare frame using data from [17]

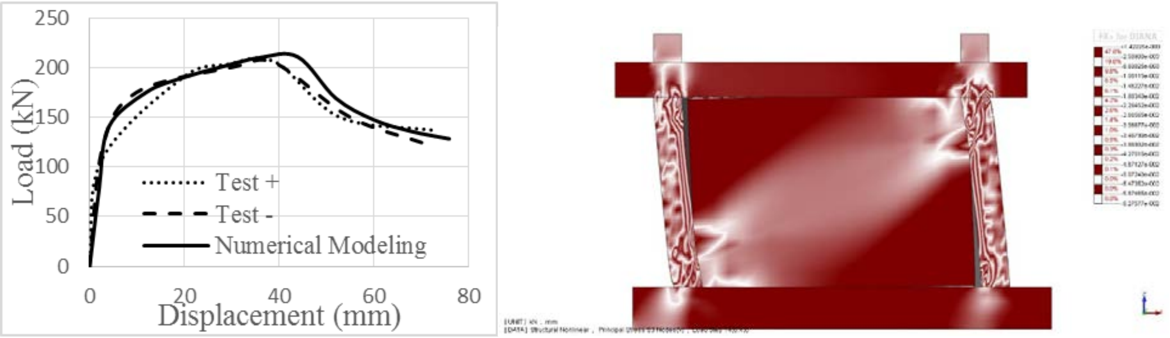
In the next step, the masonry infilled frame (specimen IF) was modeled. To simulate the contact behavior between the infill wall and surrounding frame, interface elements were introduced in those areas. The mechanical properties of interface material were calculated based on the formula proposed by Al-Chaar and Mehrabi [18]. Some of these parameters were calibrated by validating the numerical lateral force-displacement curve of the specimen IF in comparison to the experimental curve. Table 3 illustrates the interface parameters and their adopted values.

Tab.3: Mechanical properties of the interface elements

Parameters defined in interface model	Definition	Values
K_{nn}	Normal stiffness modulus (N/mm^3)	3
K_{ss}	Shear Stiffness modulus (N/mm^3)	1.6
f_t	Tensile strength (Mpa)	0.5
G_f^I	Fracture Energy for Mode-I (N/mm)	0.03
C*	Cohesion (Mpa)	0.02
Φ*	Internal friction angle (radian)	0.078
ψ	Dilatancy angle (radian)	0.005
φ_r*	Residual friction angle (radian)	0.075
σ_u	Confining normal stress (Mpa)	-0.75
δ	Softening parameter (dilatancy degradation coefficient)	2.3
G_f^{II}	Fracture energy for Mode-II (N/mm)	0.75
f_c	Compressive strength (Mpa)	5
C_s	Shear traction contribution to the failure	1
G_{fc}	Compressive fracture energy (N/mm)	4
κ_p	Relative plastic displacement at peak compressive strength (mm)	0.15

* calibrated parameters by validating the numerical modeling based on the experimental results

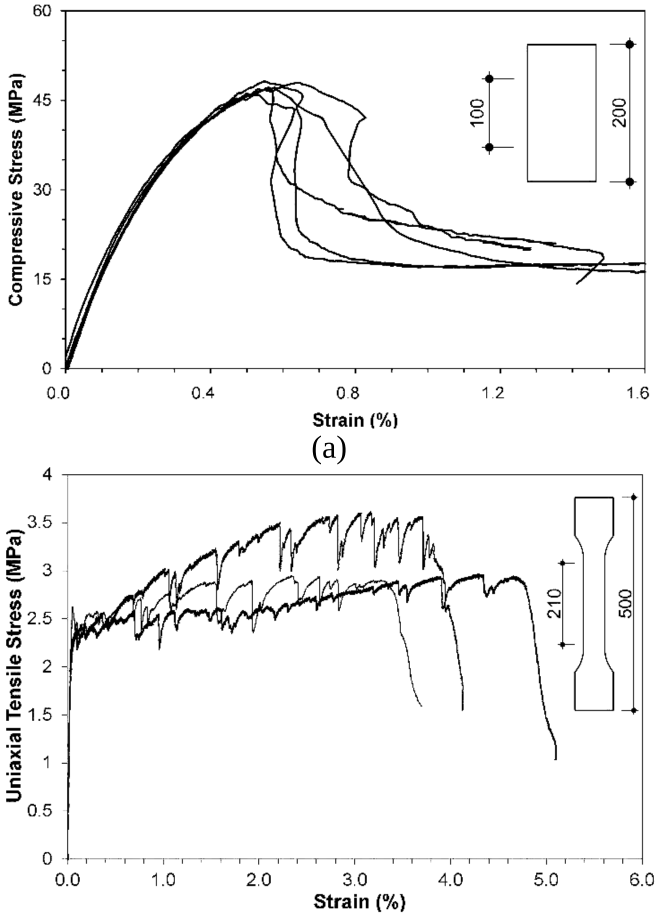
The main results obtained from IF model is shown in Figure 4. It can be stated that the numerical lateral force-displacement curve for this specimen roughly coincides with the test results. figure 4-a proves that the model succeeds in predicting the initial stiffness and load carrying capacity of the brick infilled frame as well as the descending branch of load-displacement curve. At small lateral drifts, masonry infill and its surrounding frame act as a monolithic load resisting system. However, by increasing the lateral drifts masonry infill separates from its bounding frame and forms a diagonal strut as shown in Figure 4-b to withstand the applied load. Separation between the masonry and RC frame occurred in the left upper corner at lateral load of 90KN and in the right bottom corner at lateral force of 150KN.



(a) (b)

Fig. 4: (a) comparison of the numerical force-displacement diagrams with the monotonic experimental envelop of IF specimen and (b) distribution of principal stresses within infilled frame

In the last step, Specimen IF-DL15 was modeled, considering interface elements between the infill wall and ECC retrofitting layers. In order to model ECC material, the compressive and tensile stress-strain behaviour of ECC were introduced directly to the numerical model. These were found as the average results of uniaxial compressive and tensile tests on cylindrical and dog-bone shaped specimens, respectively, as shown in Figure 5. The ECC cylinders had exhibited an average compressive strength of 47 MPa at a strain level of 0.55% and the tensile specimens had shown an average crack strength of 2.45 MPa and strain capacities from 3.3% to nearly 4.7% during the tests [15].



(a)

(b)

Fig. 5: (a) compressive behavior of ECC and (b) stress–strain behavior of ECC in tension [15]

The experimental envelope curve of specimen IF-DL15, shown in figure 6-a, reveals that the retrofitted infilled frame has an elastic behavior up to 1.8 mm of lateral displacement corresponding to a load of 100 kN. The experimental study showed that in low lateral loads, the cracks occurred in ECC layer and no cracks appeared in the RC frame nor in the retrofitted infill wall. By increasing the lateral displacement, the primary cracks formed at the column-infill wall interface and the nonlinear behaviour of the system was initiated. In the next steps, flexural cracks in the columns and multiple cracking in the ECC layer were observed and masonry infill separated from its bounding frame and formed a diagonal strut in ECC layer[15]. One of the main points in the crack formation and failure mechanism was that the ECC layer experienced multiple cracking and was damaged instead of masonry infill wall. Vulnerability of the ECC layer and masonry infill wall at the final loading step can be compared with each other based on figures 7-a and 7-b. Also, it is noticeable that the corner crushing occurred in masonry wall under ECC layer and the diagonal strut was not observed like that of the masonry infill wall in IF specimen.

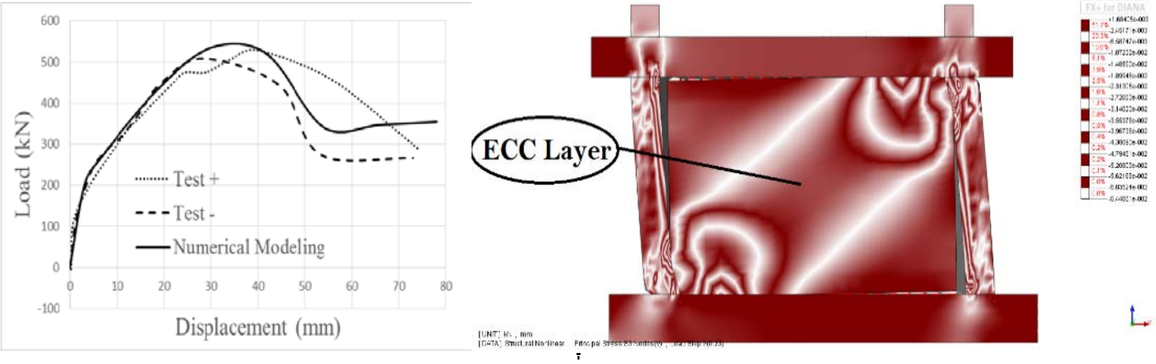
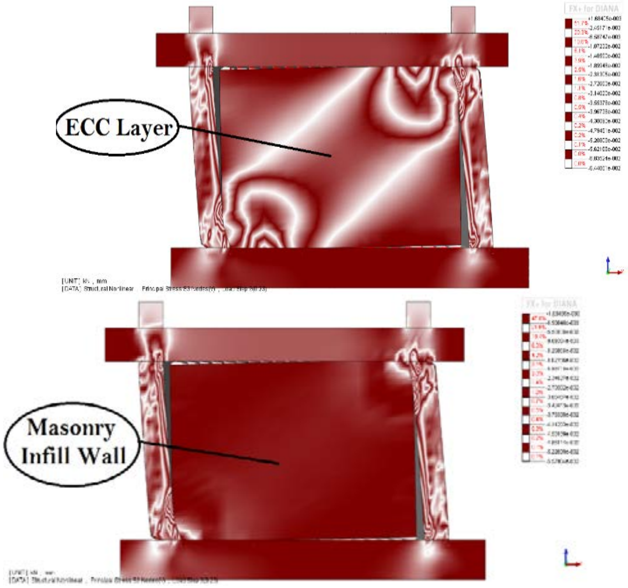


Fig. 6: Comparison of numerical and experimental results for specimen IF-DL15



(a) (b)

Fig. 7: Distribution of principal stresses within: (a) the ECC layer and (b) the infill wall under ECC layer

4. Conclusions

The numerical study presented in this paper focused on the issues involved in the numerical modeling of masonry infilled RC frames under in-plane lateral loads before and after strengthening by Engineered Cementitious Composites (ECC) material. A finite element modeling methodology was developed, calibrated, and validated with available experimental data. The proposed model combines the discrete and smeared crack approaches and considers the infill wall as homogeneous material to show all possible failure mechanisms. The model includes the smeared crack elements to simulate the cracking behavior of concrete, masonry wall, and ECC layer. Furthermore, the model adopts the interface elements between the infill wall and frame as well as ECC layer. With the consistent calibration of this modeling approach, various failure mechanisms of bare

RC frame and infilled RC frame before and after retrofitting are successfully captured. The conclusions can be summarized as follows.

- Since the bond-slip effect has not been considered in the model due to software limitations, numerical model shows a higher stiffness after initial steps up to the peak point in comparison to the experimental result. However, the modeling of bond-slip does not affect the response of the infilled frame because the collapse of such system happens in relatively lower drifts in comparison to the bare frame and the bond slip does not occur up to these levels of drifts.
- The infilled frame showed 175% and 660% increase in the load carrying capacity and initial stiffness with respect to the bare frame, respectively. The initial stiffness of the infilled frame found to be much higher than that of bare frame due to the presence of the infill wall.
- A diagonal strut in IF specimen is formed in the homogeneous masonry material that can be used in macro models.
- The failure mechanism of masonry infilled RC frame changes after strengthening with ECC because the diagonal strut develops within the ECC layer rather than the brick wall.

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