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Infill wall effect on seismic response of reinforced concrete moment resisting frame

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Abstract— All across the world, structures with reinforced concrete (RC) frames and unreinforced masonry (URM) infill walls are frequently constructed. (URM) infill walls are widely used as non-structural components, URM infill walls have an impact on both the structural and non-structural performance of RC buildings. Infill walls influence the structure's response to earthquakes and can have either positive or negative impacts. Up to a certain amount of ground motion, infill walls help the structure's ability to resist lateral forces and dampen them. On the other hand, the fundamental period, ductility, and energy dissipation of the structure are decreased by infill walls, which improve the initial stiffness and ultimate strength of the structure. The early brittle failure of URM infill walls might result in the construction of a weak story, which can ultimately lead to the collapse of the building. Infill walls interact with the surrounding frame in a way that increases the likelihood of column shear failure. Additionally, asymmetrical placement of infill walls for practical reasons might cause torsion, which increases the demand for the columns. for these objectives, the focus of this study is on how reinforced-concrete (RC) moment frames interact with infill walls. To achieve this, a numerical analysis of RC frames will be performed to evaluate the strength and stiffness of the structures as well as the structural response.

Index Terms— Reinforced concrete (RC), unreinforced masonry (URM), Infill wall, Performance-based design (PBD), Moment resisting frame (MRF).

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1 Introduction

At least 10,000 years have passed since the first use of clay bricks. In Babylon, Egypt, Spain, South America, the United States, and other places they were made from sun-dried bricks and were commonly utilized. Older structures typically have unreinforced masonry (URM) walls. Due to their excellent impact resistance and sound and heat insulation capabilities, masonry walls are frequently employed in modern construction to fill interior and external frameworks made of steel, concrete, or both. Due to their proven tolerable performance and durability regarding temperature, noise, moisture, and fire, these walls—known as masonry infill walls—represent the oldest type of enclosure system.

Reinforced concrete (RC) structures constitute a significant portion of the building inventory. The desire to separate a building's interior space from its surrounding environment naturally leads to the need to arrange infill walls in framed constructions. Using brick infill walls provides a cost-effective and long-lasting option. They are simple to construct, aesthetically pleasing and have excellent cost-performance ratios. As a result, RC frame structures often use masonry infill walls, a widely used construction method in residential and commercial structures.

There are numerous ways to fill the frame structure thanks to the combination of various masonry units made of various materials and various mortars. Ceramic bricks composed of clay are the most popular type of material used to build masonry infills, followed by concrete blocks, autoclaved aerated concrete (AAC), calcium silicate (CS), etc.

Since reinforced concrete frames with masonry infill walls are a common type of construction in seismic regions all over the world, all these facts are crucial to the theme of this study. Infilled frames, however, have not benefited from construction practices from the middle of the 20th century until the present. As a result, modern RC frame constructions with infill walls were created without taking seismic action into account.

Additionally, infill walls within frame buildings have typically been viewed as non-structural parts and so have not been given the same consideration as structural elements due to the complexity of the problem and the lack of a realistic, yet simple analytical model.

According to Comite Euro-International Du Beton (1996), infill increases the stiffness of the bare frame by 4 to 20 times, which means that infills cannot be neglected in the design process because they increase lateral stiffness and consequently shorten the frame's natural period of vibration, which increases accelerations and inertia forces (Figure 1).

A bare frame without infill walls deflects under horizontal stresses by bending its beams and columns. Infill panels reach their maximum load capacity extremely quickly, however, this is followed by a sharp decline in strength because of their low drift capacity and rather stiff and brittle in-plane response. Thus, it can be said that infills sustain damage when inter-storey drift values are low. Infilled frame's strength is increased by the infill wall, but its ductility is much reduced.

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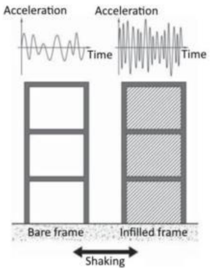

Figure 1 Comparison of roof-top accelerations of a bare and infilled frame [5]

2 Literature Review

The behaviour of infilled frames has been the focus of study projects by scientists from all around the world. Although there has been a lot of work done since the middle of the 20th century, the scientific interest in the seismic response of masonry infills has significantly expanded in recent years because of the topic's practicality.

Numerous studies [1]; [2] demonstrate the fact that masonry infills cannot withstand the high deformability of RC frames without experiencing a rather brittle response characterized by a sudden decrease in resistance, which can lead to severe damage, possibly even disintegration or partial collapse of the wall. This is further supported by FEMA 154 (2002), which awards concrete frame buildings with URM infill walls the lowest Basic Structural Hazard Score. Also, El-Dakhakhni [3] concluded that URM infill walls perform poorly even during moderate earthquakes. This implies that even in the case of masonry infills in recently built buildings, deterioration from infills may considerably contribute to financial losses and pose serious risks to human life.

Despite all the drawbacks of conventional infill walls, research has shown that masonry infill walls can improve the seismic performance of reinforced concrete structures. Infills can greatly boost the energy dissipation capacity and minimize the maximum displacements, according to Liberatore et al 's research [4]. However, it is important to prevent any potential adverse impacts of the frame/infill interaction that could result in severe damage to both RC frames and masonry infill walls. Charleson [5] also confirms the positive impact of infills, but only in the context of low-rise buildings, continuous infill panels from the foundation to the roof, and symmetrically arranged in the plan.

2.1 In-plane behavior of infill walls

Numerous studies have investigated the behaviour of masonry-filled frames that are subjected to in-plane lateral loads using both numerical and experimental methods. This section provides an overview of the in-plane behaviour of infills as well as the key findings that affect their in-plane response to seismic excitation.

Three phases may be identified in the in-plane behaviour of infilled frames, the first of which corresponds to small displacements and is distinguished by a high initial stiffness relative to the bare frame. Since there are no cracks at this stage, the infilled frame functions as a single monolithic composite structure. It is important to note that numerous researchers have identified an increase in stiffness and the consequent change in the period of the structure due to the infills, including [6], [7], [8], and [9]. Within the first phase, change in the structure's fundamental period is specifically investigated.

As long as the load is applied, the first cracks begin to appear, which causes the lateral stiffness to decrease. The start of the inelastic behaviour is also shown in this phase. The loaded di- agonal of the panel contracts during this phase, while the non- loaded diagonal corners produce gaps between the frame and the infill because the infill and the frame have different defor- mation modes. In phase three, behaviour is based on the model of infill failure and the frame's behaviour. The infilled frame now exhibits significant energy dissipation when subjected to cyclic loadings. The infill sliding and cracking is the main factor in energy loss. The value of strength and stiffness tend to decline with increasing drift, cycle by cycle until the degree of damage to the infill is so great that it makes little difference tothe system.

2.2 Failure modes of infill panel

- Compression failure in the corners. The failure of the compression strut causes corner compression failure or corner crushing failure mode to take place. When weak infills are flanked by strong columns and beams and have weak infill-frame interface joints, it causes stressed corners to crush.
- The center of the infill is damaged due to the infill panel buckling, which takes place as the center of the wall is crushed. This mode typically arises in narrow infills where out-of-plane deformations coexist with in-plane loads.
- Shear failure along the bed joint. when poor quality mortar is utilized and the infill aspect ratio is low, shear failure along the bed joint is the mechanism that frequently happens. In this mechanism, one or more bed joints experience breaking.
- Diagonal tensile failure. on the diagonal compression strut, diagonal tensile failure manifests as cracks that spread along the bed and head joints, typically forming a stepped diagonal fracture. When bricks are stronger than mortar, this mode may take place. On the other hand, bricks can also crack. Shear sliding and diagonal cracking may manifest in a mixed form.

From the pervious studies, its clear that infill wall has an effect on lateral behaviour of RC frames.in this paper, finite element model of RC infilled frame created and valiadted against experiment results. then parametric study conducted to simulate the beahviour of infilled frame under lateral loads.

3 Numerical Analysis and Validation

This section describes the modeling of one storey, single-bay infilled frame constructed to a reduced scale of ¾ and tested by Crisafulli [10] under pseudo-static cyclic loadings. Actuators have been used to apply lateral and vertical forces, simulating thus the gravity loads and overturning moment corresponding to a typical two-storey building with infill panels.

3.1 Test setup

Two steel columns joined at the top by a steel beam made up the loading frame. The columns were stiffened at the level where the lateral forces were applied using two diagonal braces. The laboratory floor was attached to the base of the columns and the braces. Using eight steel rods with a diameter of 8 mm and four RHS steel beams to secure the ends of the rein-

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forced concrete base, the test units were fastened to the floor.

Two hydraulic actuators loaded with a continuous 120 KN force compressed the base between the steel columns to prevent it from moving horizontally. At each side of the unit, an RHS steel beam was placed to prevent out-of-plane displacement. Two hydraulic actuators were used to apply the lateral forces to the devices, which were located 2.50 m from the testing floor. Vertical forces of 20 KN were applied at the top of each column to imitate the effects of gravity loads.

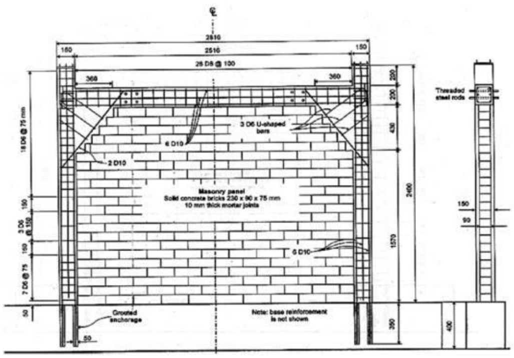

Figure 2 Infilled Frame [10]

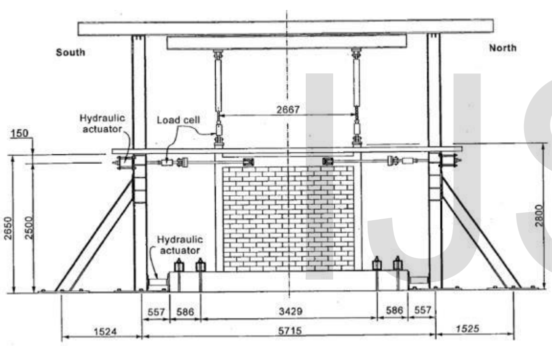

Figure 3 Layout of the in-plane setup for cyclic static tests[10]

3.2 Material characterization

3.2.1 Concrete and steel reinforcement properties

The mean concrete strength, measured after 28 days, was 31.2 MPa, while the elastic young's modulus was about 26252.77 MPa. The reinforcement steel bars had a medium strength of 323 MPa.

3.2.2 Masonry unit and mortar properties

Solid concrete bricks, with dimensions 230x90x75 mm were used for the construction of the masonary panels. Masonries used to arrange the specimens were subjected to experimental tests to assess their mechanical properties. All the significant results in terms of mechanical elastic properties and strengths.

3.2.3 Calibration with FE models

To verify the global response of the specimen, the SeismoStruct model was used to simulate the following:

- Hysteretic behavior of time history static quasi-static loading.
- Whole structure capacity.
- Pinching effect.
- Degradation of stiffness of the whole specimen during loading.

SeismoStruct is a Finite Element structural analysis tool that can simulate how space frames will respond to large displacements under static or dynamic loadings while accounting for both geometric nonlinearities and material inelasticity.

3.2.4 Geometry

- Single story-one bay RC frame specimen of clear span2.660 m and height 2.10 m.
- RC Column (0.15 X 0.15) m
- RC Beam (0.15 X 0.20) m
- Infill of thickness =0.09m

3.2.5 Concrete Material

Concrete and steel materials for various elements were defined as provided in the verification paper. The Mander et al. of the concrete model is employed for defining the concrete material with characteristic parameters: fc=31200 kpa, ft=0 kpa, εc=0.002 m/m

3.2.5 Reinforcement Material

The parameters for the steel model are listed in Table 1.

Table 1 Parameter used for steel modeling

Parameter	Value
Young's modulus (Es)	200GPa
Yield strength (Fy)	521MPa
Strain hardening parameter	0.006
Transition curve initial shape parameter R0	20
Transition curve shape calibrating coefficient–A1	18.5
Transition curve shape calibrating coefficient–A2	0.15
Isotropic hardening calibrating coefficient – A3	0
Isotropic hardening calibrating coefficient – A4	1
Fracture/buckling strain	0.15

3.2.6 Modelling and Loading

Columns and beams are modeled through 3D force-based inelastic frame elements (infrmFB) with 8 integration sections. The number of fibers used in section equilibrium computations is set to 200. Reinforced Concrete sections are defined exactly as a sketch of RFT in Figure 2 The infill panel is modeled through a four-node masonry panel element (inelastic infill panel element) as shown in Figure 4

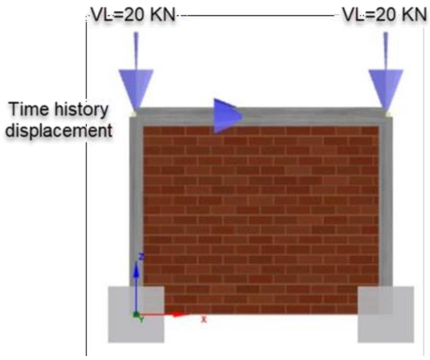

Figure 4 Seismo-struct model

3.2.7 Infill parameters

Table 2 Infill parameters

Strut Curve Parameters		
initial Young modulus (Kpa)	Em	1100000
compressive strength	fmΘ	950
tensile strength	ft	0.01
strain at maximum stress	ξm	0.001
ultimate strain	ξu	0.02
closing strain	ξcl	0.002
strut area reduction strain	ξ1	0.0004
residual strut area strain	ξ2	0.0008
starting unloading stiffness factor	γun	2
strain reloading factor	αre	1.5
strain inflection factor	αch	0.6
complete unloading strain factor	βa	2
stress inflection factor	βch	0.7
zero stress stiffness factor	γplu	1
reloading stiffness factor	γplr	1.1
plastic unloading stiffness factor	ex1	1.5
repeated cycle strain factor	ex2	1
Shear curve parameters		
shear bond strength		50
friction coefficient	μ	0.2
maximum shear resistance		200
reduction shear factor	αs	1.6
General		
Panel thickness	t	0.09
out-of-plane failure drift		0.05
strut Area 1 (tw*bw)	A1	0.1
strut Area 2	A2	0.7
Equivalent contact length	hz	0.07
horizontal offset	x0	0.05
vertical offset	y0	0.05
Proportion of stiffness assigned to shear	γs	0.5
specific weight (KN/m3)	γ	10

3.2.8 Applied Loads

- Two Concentrated loads (20 KN) are applied on the top node of each column to represent vertical loads applied through jacks in the experiment setup.
- Displacement with specific time history displacement as mentioned above.
- Displacement loading type: Static time history.

3.2.9 Modeling Evaluation

In this section, the numerical cyclic response obtained from the modeling of one bare frame and three infilled frames is evaluated with experimental data results. A comparison between analytical and experimental results is conducted regarding cyclic response, peak load, hysteretic shape, and pinching behavior. As a measure for the evaluation, the error in the results will be the ratio between the difference between the analytical and experimental results to the experimental value.

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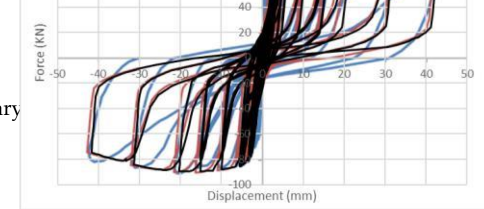

Figure 5 Force Displacement curve

This curve shows the cross-validation with Experimental re-sults by Crisafulli [10] in blue color and numerical results byRooshenas [11] in orange color with my numerical analysisresults in black color.

3.2.9.1 Ultimate Strength

Table 3 Ultimate Strength

Specimen No.	Experimental Load (KN)			Analytical Load (KN)			Difference
	Qu_{+vve}	Qu_{-vve}	Mean	Qu_{+ve}	Qu_{-ve}	Mean	
IF	90	-92	91	89.7	-89.6	89.7	1.49%

3.2.9.2 Displacement at Ultimate Strength

Table 4 Displacement at Ultimate Strength

Specimen No.	Experimental Displacement(mm)			Analytical Displacement(mm)			Difference
	$\Delta fmax_{+ve}$	$\Delta fmax_{-ve}$	Mean	$\Delta fmax_{+ve}$	$\Delta fmax_{-ve}$	Mean	
IF	16	-21	18.5	16.3	-19.1	17.7	4.44%

3.2.9.3 Maximum Displacement

Table 5 Maximum Displacement

Specimen No.	Experimental Displacement(mm)			Analytical Displacement(mm)			Difference
	Δmax_{+ve}	Δmax_{-ve}	Mean	Δmax_{+ve}	Δmax_{-ve}	Mean	
IF	42	-43	42.5	42.72	-41.7	42.2	0.66%

3.2.9.4 Force at Maximum Displacement

Table 6 Force at Maximum Displacement

Specimen No.	Experimental Load (KN)			Analytical Load (KN)			Difference
	FΔmax +ve	FΔmax -ve	Mean	FΔmax +ve	FΔmax -ve	Mean	
IF	72	-81	76.5	74	-74.53	74.2	2.99%

4 Parametric analysis program

The created numerical model described in section 3 is used for a parametric study that is presented in the following once it has been appropriately calibrated and validated using experimental data. On infilled frames, parametric research is conducted to analyze how they respond to changes in mechanical properties, mechanical characteristics, and boundary conditions. The infill frames' many parameters include the following in further detail:

- Level of axial loading
- Concrete class.
- RC frame stiffness (frame-to-infill stiffness ratio)
- Reinforcement ratio of the frame.

4.1 Geometry

- Single story-one bay RC frame specimen of clear span 4.22 m and height 2.95 m.
- RC Column (0.35 X 0.35) m
- RC Beam (0.35 X 0.35) m

4.2 Concrete Material

Concrete material for various elements was defined in the table provided in the verification paper. Mander et al. nonlinear concrete model (con_ma) is employed for defining the concrete material with characteristic parameters: fc=28000 kpa, ft=0 kpa, εc=0.002 m/m

4.3 Reinforcement Material

The steel reinforcement was modeled using Menegotto-Pinto (1973) steel model (stl_mp) which is a uniaxial steel model coupled with the isotropic hardening's rules, this model is defined by Modulus of elasticity, yield strength, strain hardening parameter, fracture/buckling strain and some coefficients representing Baushinger effect, pinching of hysteretic loops and transition from elastic to the plastic zone.
The parameters for the steel model are listed in Table 7.

Table 7 Parameter used for steel modeling

Parameter	Value
Young's modulus (Es)	200GPa
Yield strength (Fy)	521MPa
Strain hardening parameter	0.006
Transition curve initial shape parameter R0	20
Transition curve shape calibrating coefficient–A1	18.5
Transition curve shape calibrating coefficient–A2	0.15
Isotropic hardening calibrating coefficient – A3	0
Isotropic hardening calibrating coefficient – A4	1
Fracture/buckling strain	0.15

4.4 Results

4.1.1 Level of axial loading.

In the following, the influence of the vertical load level on the columns is investigated. Simulating loads from the upper stories of a building. Vertical forces of 200kN .400 kN and 600kN per column. Figure 6 shows the increase of maximum load level for higher vertical loads for different infill materials.

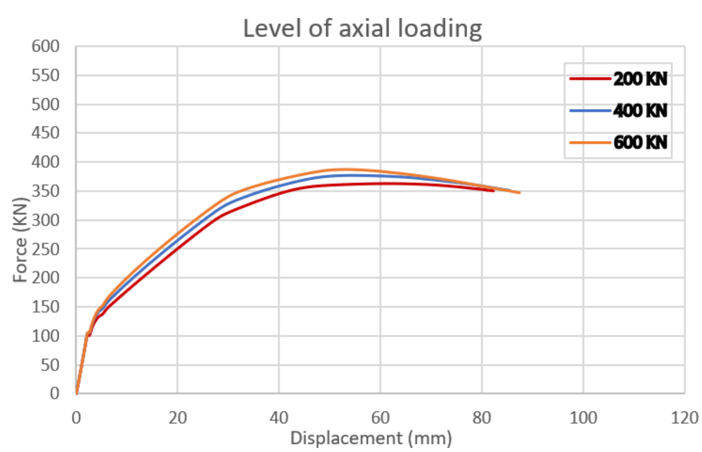

Figure 6 Level of axial loading.

4.1.2 Concrete class.

The influence of concrete strength on the behavior of infilled frames has been also investigated. Numerical models of three concrete classes C30/37, C40/50, and C50/60 have been studied. Figure 7 shows that the concrete class slightly increases the capacity of the infilled frame

Figure 7 Concrete class.

4.1.3 RC frame stiffness (frame-to-infill stiffness ratio).

Besides the infill stiffness and the dimensions of the RC frame, the cross sections of the columns and the top beam influence the frame-to-infill stiffness ratio. The experimentally tested frame had columns of 35x35cm and a top beam of 35x35cm. To study the influence of the frame stiffness, an additional simulation with quadratic cross sections of 40x40 cm and 45x45 cm for columns and the top beam is carried out.

Figure 8 shows that the increase of the column and beam dimensions leads to an increase in the initial stiffness and maximum load. It can be concluded that frame stiffness is an important parameter as it directly influences
the maximum load capacity of the bare frame and the displacement demand generated by the RC frame system.

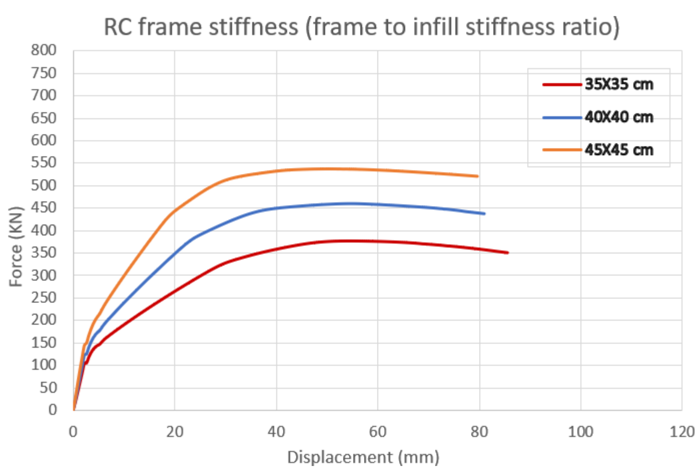

Figure 8 RC frame stiffness (frame-to-infill stiffness ratio).

4.1.4 Reinforcement ratio of the frame.

Another characteristic investigated is the reinforcement ratio of the RC frame. The reinforcement ratio of the experimentally tested frame was 2.05% for columns. Two additional simulations are executed, where only the cross sections of the longitudinal bars were changed, giving the reinforcement ratios as presented in Table 8. From Figure 9 it can be concluded that the change in the reinforcement ratio influences the infilled frame response.

Table 8 the reinforcement ratios of infilled frames

Model	RFT	Column
IF1	8T16	1.31%
IF2	8T20	2.05%
IF3	8T25	2.48%

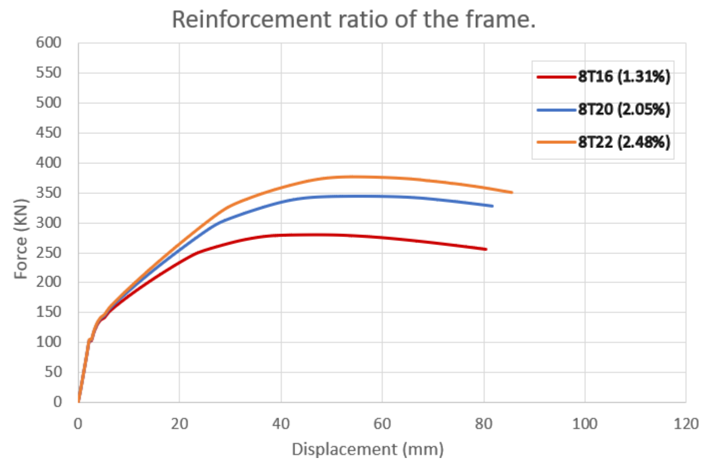

Figure 9 Reinforcement ratio of the frame.

5 Conclusions

This paper focuses on the behaviour of RC frames with infill walls during earthquake excitation. For this, the numerical model was developed and validated against experimental results. The validated model was further used to study various parameters to capture their effect on the seismic response of the RC frames. The conclusions as below:

1. The increase of maximum load level for higher vertical loads.
2. The increase in the column dimensions leads to an increase in the initial stiffness and maximum load.
3. The frame stiffness is an important parameter as it directly influences the maximum load capacity of the bare frame and the displacement demand generated by the RC frame system.
4. The change in the reinforcement ratio influences the Infilled frame response
5. The concrete class slightly increases the stiffness of the model, but it does not influence the drift level when the cracking of the infill starts.

6 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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