Multi-platform simulation of infilled shear-critical reinforced concrete frames subjected to earthquake excitations

Xu Huang¹ · Alex Brodsky²

Received: 11 November 2021 / Accepted: 7 April 2022 / Published online: 26 April 2022
© The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract
This paper proposes a multi-platform simulation method for the seismic performance assessment of masonry infilled reinforced concrete (RC) frames, especially for those that, due to inadequate reinforcing details, tend to undergo shear failure during an earthquake. The multi-platform method is based on a micro–macro modeling approach in which a detailed finite element model of the RC frame is incorporated with a strut model of the infill wall. It exploits the strut model to increase its computational efficiency and the finite element model based on the modified compression field theory to capture the nonlinear behaviour of the RC frame. The proposed method is validated against previously tested frames subjected to lateral loads, and its advantages over the conventional strut models are demonstrated through both quasi-static and dynamic analyses.

Keywords Masonry infill walls · Reinforced concrete · Infilled frames · Multi-platform simulation · Earthquake loading · Shear

1 Introduction

Reinforced concrete (RC) frame structures with infill walls are used widely all over the world. The infill walls were usually neglected during the structural design process since they were considered non-structural elements. The findings of several studies, however, indicate that the infill walls increase the structure’s stiffness, decrease its natural period, frequently increase its capacity, and reduce its ductility. Moreover, the RC frame’s interaction with the infill wall during lateral deformation may alter the frame’s failure mode compared to that of a bare frame.

* Alex Brodsky
alexbrod@bgu.ac.il

¹ Department of Civil and Mineral Engineering, University of Toronto, Toronto, Canada
² Department of Structural Engineering, Ben-Gurion University of The Negev, Beer Sheva, Israel
1.1 Frame failures during earthquakes

Partial infill walls refer to walls that are shorter than the columns or to walls with built-in openings beside the columns. If these walls are not adequately isolated from the surrounding frame, they have a negative effect on the lateral response of the structure. Specifically, the presence of the partial infill wall constrains the lateral deformation of the columns by decreasing their clear heights, i.e., the distance from the top of the infill wall to the bottom of the upper beam or the floor above. Consequently, it significantly increases the shear demands of the columns, and a shear failure typically occurs, as shown in Fig. 1. This behavior is well known as the short column effect.

Even if the infill wall is built all over the column’s height, shear failure of the frame may still happen, as shown in Fig. 2. During earthquakes, the structure deforms laterally, and parts of the infill wall detach from the surrounding frame when other parts are in contact. The frame is subjected to non-negligible interfacial interaction stresses at the frame and infill wall contact regions. These stresses increase the flexural and the shear demands on the RC frame elements. If the frame columns were not designed for these additional loads from the infill wall, they tended to fail during strong earthquakes (Fig. 2). A detailed field survey performed after the 2015 Gorkha Earthquake (Brzev et al. 2017) revealed that this type of shear failure of the RC columns could be devastating. It led to a loss of the column’s gravity load-carrying capacity and a progressive collapse of the structure, as shown in Fig. 3.

Other commonly seen failure modes of infilled frame structures include the failure of the ground floor columns because this floor is frequently the only floor that is lack of...
infill walls. This mode is the so-called soft-story mechanism because of vertical irregularity (Agha Beigi et al. 2015). Torsional failure modes were observed because of horizontal irregularity (Suzuki et al. 2021; Hareen and Mohan 2021), for example when the infills significantly violated the symmetry in the structure in such a way that the centre of mass did not coincide with the centre of stiffness. During strong earthquakes, the infill walls could crush, detach, and fall out of the surrounding frame (Pasca et al. 2017, Lu et al. 2020). Aside from the fact that the out-of-plane collapse of the infill walls is very dangerous for those standing around the building, it may lead to horizontal and vertical irregularities and their associated failure modes.

1.2 Challenges in modeling infilled frame failure

The recurring failures of infilled frames during earthquakes led to changes in the current seismic codes’ provisions, e.g., ASCE 41 (2017). These codes typically adopt a strut model, which replaces the infill wall with a single compression-only diagonal strut. They suggest connecting the diagonal at a certain distance from the beam-column joint to account for the infill-frame interaction. While the equivalent strut approach can well represent the increased stiffness of the frame and thus more reliably represent the period of the structure, its ability to represent the failure mode of the structure is still limited. This is due to the challenges associated with predicting the response of infilled RC frames that involves the nonlinear behavior of the frame, the infill wall, and the interaction between the infill wall and the frame.

1.2.1 Infill-frame interaction

The infill wall and the frame interact with each other during the loading/deformation process. Brodsky et al. (2018) investigated the infill-frame interaction using a dedicated experimental facility and found that the contact regions varied during the deformation process. In particular, significant infill cracks changed the infill-frame contact length and the stress distribution over the contact regions.

Fig. 3 Collapse of the infilled RC structure followed by a shear failure of the frame (photos: D.K. Maharjan (left) and (Karmacharya et al. 2018))
1.2.2 Infill wall

Various approaches have been developed to represent the response of the infill wall, as illustrated in Fig. 4. They range from very detailed models, such as micro-scale models where each block and mortar layer are modeled (Asteris et al. 2013; Wararuksajja et al. 2020; Erdem 2021), to simplified models, such as models based on homogenization of the infill wall, e.g. (Anthoine 1995; Kawa et al. 2008; Zucchini and Lourenço 2009; Casolo and Milani 2010), or the use of an equivalent strut or multiple struts, e.g. (Chrysostomou et al. 2002; Cavaleri and Papia 2003; Uva et al. 2012; Motovali Emami et al. 2017).

One challenge of the detailed micro-scale models is to define the mechanical parameters of the block and the mortar joints. But even when all required material tests have been performed, the use of sophisticated micro-scale models cannot always ensure accurate prediction of the wall’s nonlinear behavior and cracking pattern. It is due to high uncertainties of the material properties and the complex infill-frame interaction. Moreover, this technique requires high computational resources. Thus, it is mainly limited to small-scale frames and unsuitable for multi-story structures. The equivalent strut models, on the other hand, are more widely used due to their simplicity and efficiency.

1.2.3 RC frame

The equivalent strut models of the infill wall are usually incorporated in a RC frame modeled by fiber-section elements with either distributed or lumped plasticity (Burton and Deierlein 2014; Sattar and Liel 2016; Noh et al. 2017; Huang et al. 2020). The models allow capturing the global behavior of the entire structure. However, the complex two-dimensional stress state at the infill-frame interaction regions and the deformability of the beam-column joints cannot be well represented in these simplified models.

Due to the fundamental assumption that the cross-sections remain plane and normal to the deformed longitudinal axis, the fiber beam-column elements are incapable of capturing shear-related behavior of RC frame components during earthquakes. Therefore, additional efforts should be made to use these simplified models for shear-critical frames. For example, Burton and Deierlein (2014) and Sattar and Liel (2016) added several lumped shear springs to the ends of frame columns to account for the shear deformation and failure of the frame. The backbone curve representing the spring response was based on a combined shear limit surface proposed by Sezen and Moehle (2004) and Elwood (2004). In the study, the shear-axial failure interaction of the columns was not simulated, i.e., the axial failure and collapse were conservatively assumed to occur when the shear strength reduced to zero. Favvata et al. (2008) and Karayannis et al. (2011) developed a model for the simulation of exterior RC beam-column joints by a rotational spring element. This model requires the calibration of 12 parameters to define the inelastic response of the joint. Verderame

Fig. 4 Various modeling methods for the infill walls
et al. (2019) used the ASCE/SEI 41 (2017) code and the Simplified Modified Compression Field Theory (SMCFT) (Bentz et al. 2006) equations to predict the shear failure of the frame. In the study, they calculated the shear capacity of the frame column as a part of the post-processing procedure of the numerical analysis, which was carried out in OpenSees (McKenna 2011) with a fiber-based element. They found that the SMCFT shear failure predictions were in good agreement with the test results.

The SMCFT is the basis for shear provisions of the Canadian concrete code (2014) and the AASHTO US bridge design code (2014). But this simplified version of the Modified Compression Field Theory (MCFT) (Vecchio and Collins 1986) is a procedure that allows computing the shear strength of an element under a basic assumption that the perpendicular compressive stress (the “clamping stress”) is negligibly minor (Bentz et al. 2006). In other words, the method is only applicable to the non-disturbed sections. However, the shear-critical section is typically located at the infill-frame interaction zone where the clamping stresses are significant. Thus, the use of these equations stands in contradiction to the theory’s assumptions, and it is necessary to implement the original set of MCFT equations for the cases investigated in this study.

Another common assumption in fiber-section element models is to model the beam-column joints by rigid link elements, e.g. (Al-Chaar 2002; Trapani et al. 2021). Therefore, the models cannot explicitly account for the potential deformability and any failure of the joints. Other studies modeled the joint by zero-length artificial rotational springs, e.g., (Liel et al. 2010; Karayannis et al. 2011; Grande et al. 2021). However, most lumped spring models involve substantial approximations and calibrations as addressed by Ghannoum and Moehle (2012), Mohammad Noh et al. (2017), and Verderame et al. (2019). There is still no widely accepted method for fiber-section models to accurately define the location and behavior of the lumped springs for modeling of shear-related behavior of RC elements and the nonlinear behavior of the frame joints.

1.3 Multi-scale model

To overcome the limitations of the fiber-based element models to represent the complex two-dimensional stress state in the interaction regions, the shear deformation of the frame, and the deformability of the joints, a micro–macro approach was proposed by Brodsky (2021). Specifically, the frame is modeled by two-dimensional (2D) continuum elements, such that the 2D stress state of the RC frame elements can be explicitly considered. In addition, the constitutive behavior of continuum elements is based on the MCFT (Vecchio and Collins 1986). The MCFT is a smeared, rotating crack model that can describe the load-deformation response of RC elements subjected to general two-/three-dimensional stress conditions. Conditions of equilibrium, compatibility, and constitutive response are formulated in terms of average stresses and strains. The concrete is treated as an orthotropic solid continuum with smeared cracks where local shear stress at the crack surface is also considered. Therefore, the nonlinear behavior of the frame that involves cracking, crushing, tension stiffening, and softening of the concrete and aggregate interlocking along the cracks can be fully considered. While the RC frame is modeled by 2D elements, the infill wall is represented by a struts model considering the complexity and uncertainty of the micro-scale models as described above. In other words, this modeling technique combines two detailing levels: a macro-scale level for the infill wall and a micro-scale level for the RC frame. This micro–macro method allows the integration of various strut models with the detailed frame model. More details about the methodology and validation of the
method can be found in (Brodsky 2021). In this study, the micro–macro model is employed by modeling the infill wall with three parallel struts: one diagonal and two off-diagonal struts to account for the increase of the flexural and shear demands on the frame elements due to the infill-frame interaction.

1.4 Multi-platform simulation

The multi-platform simulation method allows the decomposition of a structural system into several substructures, each of which can be modeled independently using different analysis tools (Mortazavi et al. 2017; Huang and Kwon 2020). When applying the method to the micro–macro model of infilled frames, at least two numerical models can be developed, one for the RC frame and the other for the struts.

OpenSees (McKenna 2011) is a commonly used tool for the analysis of RC infilled frames subjected to earthquake excitations. Burton et al. (2014b) applied the peak-oriented hysteretic model developed by Ibarra et al. (2005b) and implemented it in OpenSees to describe the axial response of the equivalent struts. Cavaleri and Di Trapani (2014d) modeled the infill wall as a diagonal strut described by the hysteretic pivot model. Mohammad Noh et al. (2017) compared three different constitutive strut models available in OpenSees: Concrete01, Hysteretic, and Pinching4. They found that the Hysteretic and Pinching4 materials more accurately predicted the hysteretic response of the infill wall.

As discussed earlier, while the OpenSees model may predict the global response, it has a limited ability to model the shear failure of the columns and the deformability and damage of the beam-column joints. To deal with shear-related cracks and failures, the RC frame can be modeled according to the MCFT which showed an excellent prediction ability for shear critical RC members. In this study, the 2D FE software VecTor2 (Wong et al. 2013) that employs the constitutive relationships of the MCFT is used.

The multi-platform method combines and takes advantage of the two analysis tools (VecTor2 and OpenSees). The benefits of the method in terms of capturing the global behavior of the infilled wall-frame system and the failure mode of the RC frame are demonstrated through both quasi-static and time history analyses. In addition, the potential of the method for accurate and efficient modeling of infilled RC frame buildings is also presented.

The layout of the article is organized as follows. Section 2 presents the multi-platform approach and methodology. The validation of the multi-platform model against flexural- and shear-critical experiments is described in Sect. 3. The application of the proposed multi-platform simulation method to dynamic history analysis is demonstrated in Sect. 4. The final section summarizes the conclusions and discusses future research and applications of the method.

2 Multi-platform simulation method

In the present study, the multi-platform simulation method for seismic performance assessment of infilled frames is demonstrated by modeling the RC frame and struts with VecTor2 and OpenSees, respectively (Fig. 5). The two models are interacting with each other by transferring data at the interface nodes that are shown in the figure. These interface nodes include those at the interface boundaries between the struts and the frame, the nodes at the fixed base, as well as those where external loads are applied. More specifically, the
OpenSees model includes the struts and the external loads, and it works as the main program to solve the incremental form of the system’s equilibrium equation at a certain time step as:

\[
(K_{\text{str}} + K_{\text{Int}}) \Delta u_{\text{int}} = P - (R_{\text{str}} + R_{\text{Int}})
\]

where \(K_{\text{str}}\) is the stiffness matrix of the struts modeled in OpenSees; \(\Delta u_{\text{int}}\) is the displacement increment vector of all interface nodes. \(P\) is the external force vector; \(R_{\text{str}}\) is the restoring force vector of the struts; \(K_{\text{Int}}\) and \(R_{\text{Int}}\) are the stiffness matrix and restoring force with respect to the interface nodes of the RC frame modeled in VecTor2 (see Fig. 5b). The VecTor2 model, on the other hand, is a slave program that computes \(K_{\text{Int}}\) and \(R_{\text{Int}}\), and sends them to the OpenSees model to formulate Eq. (1). For nonlinear problems, an iterative solution scheme, such as Newton–Raphson’s method, should be used to make the unbalance force \(P - (R_{\text{str}} + R_{\text{Int}})\) close to zero. In each iteration, trial displacements at the interface nodes are sent to the VecTor2 model to update \(R_{\text{Int}}\). Due to the difficulty in retrieving the frame’s tangent stiffness matrix \(K_{\text{Int}}\) from the VecTor2 model, the initial stiffness of the frame can be used for \(K_{\text{Int}}\). It should be noted that the initial stiffness of the RC frame is only required for nonlinear iterations and the inelastic response of the frame is fully considered in the VecTor2 model. More details about the algorithm and its implementation in OpenSees and VecTor2 can be found in references (Huang and Kwon 2020; Brodsky and Huang 2021). It should be noted that the above method is not limited to OpenSees and VecTor2 programs but is also implementable to other simulation packages as long as a similar communication scheme is established between the two programs.
3 Quasi-static analysis

This section demonstrates the use of the multi-platform simulation method for the modeling of infilled frames subjected to quasi-static cyclic loading. Two infilled frames tested in previous studies are considered. One frame (S1A-2) failed in a flexural manner and the other (UB1) failed in shear.

3.1 Flexure-critical RC frame

Figure 6 shows the details of the specimen S1A-2 tested by Cavaleri and Di Trapani (2014). The frame was infilled with calcarenite masonry. Its dimensions and material properties are summarized in Fig. 6 and Table 1. The frame was fixed to the ground and loaded with a vertical load of 200 kN at the top of each column followed by a lateral load applied at the top of the frame. The concrete compressive strength and elastic Young’s modulus were 25 MPa and 25,500 MPa, respectively. The rebars had an ultimate strength of 450 MPa and an elastic modulus of 200 GPa. Since the yield strength of the rebars was not documented, it was assumed as 400 MPa. Both the simplified and multi-platform simulation methods presented above were employed for the modeling of the specimen.
3.1.1 Simplified OpenSees model

The simplified model of the S1A-2 specimen is shown in Fig. 7. The beam and columns were modeled with fiber-section elements in OpenSees with rigid offset at the beam-column joints. The uniaxial behavior of each fiber was modeled with Concrete02 hysteresis model (Yassin 1994). To account for the confinement effect, the concrete strength and concrete strain at the maximum strength of the core concrete were increased based on the method proposed by Mander et al. (1989). The longitudinal rebars were modeled as independent layers to be superimposed into the concrete fibers. The use of various formulas leads to different values of the equivalent width and thus different strut stiffness. For example, Liberatore et al. (2018) found that the equation in FEMA 306 (1999) that initially proposed by Mainstone (1971) gives a much more deformable infill/strut compared to other models as it estimates the infill’s secant stiffness up to the ultimate strength. Moreover, FEMA suggests a simplified and conservative elasto-plastic constitutive law mainly for design purposes. In this study, to better capture the inelastic behavior of the infill wall, the multi-linear law with hysteretic properties calibrated from the experimental observation was used for the S1A-2 specimen. Specifically, the infill wall was represented as truss elements with Hysteretic material model in OpenSees to capture the nonlinear cyclic response, including pinching and strength/stiffness degradation. The behavior of each truss element was characterized by the following parameters:

- Equivalent width of the infill wall, \( w \). Based on the method proposed by Papia et al. (2003), the equivalent width of the wall can be determined from

\[
 w = d k c \frac{1}{z (\lambda^*)^\beta}
\]

where \( d \) is the diagonal length of the strut; \( k \) is a coefficient for the effect of the vertical load on the frame columns. \( c \) and \( \beta \) are parameters based on the diagonal Poisson’s ratio \( (\nu_d) \) of the infill wall; \( z \) is a shape coefficient and it equals to 1.0 for a square infill wall; \( \lambda^* \) is a parameter related to the material and geometry of the frame. For the three-strut
model considered in this study, half of the calculated width was assigned to the diagonal truss element and quarter to each off-diagonal truss element, as shown in Fig. 7.

- Contact length, $L_c$. This parameter indicates the locations of the off-diagonal struts as shown in Fig. 7 and allows considering the interaction between the infill wall and the surrounding frame. It was estimated using the method proposed by Paulay and Priestley (1992) as 0.25 times the diagonal length of the infill wall.

- Envelope parameters, $S_1$, $S_2$, $S_3$, $\delta_1$, $\delta_2$, and $\delta_3$, as shown in Fig. 8. The struts are compression-only elements, and the envelope of their response is idealized as a trilinear curve, including the initial elastic branch ($S_1 - \delta_1$), post-yielding branch ($S_2 - \delta_2$), and degradation branch ($S_3 - \delta_3$). These envelope parameters were estimated according to Cavaleri and Di Trapani (2014).

- Hysteretic material model parameters, $p_x$, $p_y$, $d_1$, $d_2$, $beta$. These parameters describe the strength/stiffness degradation and pinching behavior. Their values were adopted from Wijaya et al. (2020) who calibrated them against experimental results.

The above parameters that defined the truss elements in the simplified OpenSees are listed in Table 2.
3.1.2 Multi-platform OpenSees-VectoR2 model

The multi-platform model of the S1A-2 specimen was the same as the simplified OpenSees model except that the RC frame was modeled in detail with VecTor2 software. Specifically, two-dimensional continuum elements were employed to model the beams, the columns, and the joints. As shown in Fig. 5, the longitudinal rebars were modeled with truss elements while the transverse reinforcement was smeared with the concrete elements. Table 3 lists the material models used in the VecTor2 model for the concrete, reinforcement, and their bond. These are default models that are determined based on validations against static and dynamic tests (Vecchio and Shim 2004; Palermo and Vecchio 2007), and they are found to be able to provide reasonable predictions without much calibration effort. As the main integration module, the OpenSees model included the strut elements for the infill wall as well as the external loads applied to the frame. The VecTor2 model acted as the substructure module to compute the restoring forces based on the displacements predicted from the OpenSees model. Data were exchanged between the two models through the interface nodes, as indicated in Fig. 5. Each interface node had two translational degrees of freedom.

3.1.3 Simulation results

Figure 9 shows the experimental and numerical cyclic responses of the S1A-2 specimen. Both the simplified OpenSees and the multi-platform OpenSees-VectoR2 models were in good agreement with the experimental result. As observed in the test, the RC frame developed flexural (i.e., horizontal) cracks at the columns at large lateral displacements. Such flexural behavior was properly captured by both fiber-section and continuum elements. In addition, diagonal cracks were observed at the beam-column joints in the cyclic test. Such damage was only captured by the VecTor2 model. This increased flexibility due to the damage at the beam-column joints was not taken into account in the simplified OpenSees

| Material property     | Model                                               |
|-----------------------|-----------------------------------------------------|
| Concrete model        |                                                     |
| Concrete compression pre-peak response | Hognestad Parabola (Vecchio 1982)                  |
| Concrete compression post-peak response | Modified Park-Kent (1982)                          |
| Concrete compression softening | Vecchio (1992a),(1992b)                            |
| Concrete tension stiffening | Modified Bentz (2003) (Bentz 2005)                |
| Concrete tension softening | Linear                                             |
| Concrete confined strength | Kupfer/Richard Model (1928, 1969)                 |
| Concrete dilation     | Variable isotropic (Montoya et al. 2006)           |
| Concrete cracking criterion | Mohr–Coulomb (Stress)                             |
| Concrete crack slip check | Walraven (1981)                                   |
| Reinforcement model   |                                                     |
| Hysteretic response   | Elastic-Hardening                                   |
| Dowel action          | Tassios (Crack Slip) (He and Kwan 2001)            |
| Buckling              | Akkaya (2019)                                       |
| Bond model            |                                                     |
| Concrete bond         | Eligehausen (1982)                                 |

Table 3 Material models in VecTor2

---

---

---

---

---
model due to the rigid beam-column joints assumption. However, the deformations of the joints had a minor impact on the base shear when the frame was imposed with the same lateral displacements. As will be addressed in Sect. 4, the rigid beam-column assumption could lead to inaccurate prediction in seismic response of the same specimen during real earthquake excitations.

Figure 10 presents the patterns and widths of the main cracks at different displacement stages of the analysis of the multi-platform model. The cracks were plotted on a deformed shape of the frame with a magnification factor of five. This figure shows the evolution of the cracks at the peak positive displacements (i.e., the frame deforms to the right) of the last four loading cycles (+10, +20, +30, +40 mm). The deformed shape along with the cracking pattern for negative displacements is roughly a mirror image of Fig. 10. The widest crack developed at the location between the top end of the left column and the beam-column joint. At each loading cycle, the width of this crack increased from 4.4 mm at a lateral displacement of +10 mm to around 21 mm of the final cycle, at a displacement of 40 mm. Additional noticeable cracks were diagonal at the upper beam-column joint, which was 2.3 mm wide at a lateral displacement...
of + 10 mm and opened to 4.5 mm at a displacement of + 40 mm. In addition, both columns cracked at their connections to the bottom beam. At a displacement of +40 mm, the width of these cracks on the tension side was about 14 mm. Thus, at this stage, plastic hinges developed at the ends of the columns.

### 3.2 Shear-critical RC frame

Figure 11 illustrates specimen UB1 tested by Gao et al. (2018) at the University of Buffalo. The specimen’s columns were designed with insufficient transverse reinforcement. Therefore, the columns tended to fail in shear due to the lateral load. The frame was filled with regular double-wythe clay bricks. The material properties of the frame and infill wall are summarized in Table 4. Before imposing the lateral load, the frame was loaded with a distributed load along the top surface of the beam to simulate the gravity load from the above stories. The total applied vertical load was 338.1 kN.

![Image](image-url)
3.2.1 Multi-platform OpenSees-VecTor2 model

To demonstrate the capability of the multi-platform simulation method to predict the shear damage of the RC frame, a pushover analysis was conducted and compared with the cyclic backbone curve obtained from the experimental test. Since the load was applied in one direction, a single set of three struts was included to simulate the response of the infill wall (Fig. 12). The RC frame was modeled with VecTor2 where the longitudinal rebars were modeled with truss elements and the transverse reinforcement was smeared within the concrete elements. The interface nodes for data exchange between the OpenSees and VecTor models included those at the ends of the struts, at the loading points, as well as at the fixed base of the frame. The monotonic behavior of the struts was controlled by the effective length \( w \), contact length \( L_c \), and the envelope parameters \( S_1, S_2, S_3, \delta_1, \delta_2, \) and \( \delta_3 \) in Fig. 8). Since not all the mechanical properties listed in Table 1 are available for specimen UB1, the model parameters of this specimen were determined based on the model by Bertoldi et al. (1993) and are summarized in Table 5. A standalone OpenSees model of the UB1 frame with the same struts’ parameters was also developed for comparison.

| Parameters | Unit | Value |
|------------|------|-------|
| \( w \)    | mm   | 622   |
| \( L_c \)  | mm   | 383   |
| \( S_1 \)  | MPa  | 3.662 |
| \( S_2 \)  | MPa  | 4.577 |
| \( S_3 \)  | MPa  | 1.602 |
| \( \delta_1 \) | mm/mm | 1.611E-04 |
| \( \delta_2 \) | mm/mm | 8.054E-04 |
| \( \delta_3 \) | mm/mm | 2.698E-02 |

Fig. 12 Multi-platform model of specimen UB1
3.2.2 Simulation results

Figure 13 compares the predicted pushover curves with the measured cyclic curve. The experimental observations show that the frame reached the peak strength of about 535 kN at a drift of 0.2%. Meanwhile, noticeable shear cracks were observed, followed by a significant strength degradation. Similar behavior was predicted in the OpenSees-to-VecTor2 model, where the peak strength of 500 kN was predicted at the drift of 0.22%. Then the transverse reinforcement at the left column yielded. The predicted strength degradation was less significant than the experimental result due to accumulative damage from cyclic loading. One of the main reasons for using the multi-platform approach is to capture the shear failure of the frame without any tedious calibration of the concrete material model or lumped-plasticity models. Figure 14 compares the observed crack pattern at the end of the test with the predicted pattern from the multi-platform model. The model well captured the shear failure mode. At a drift ratio of 1%, the main cracks were diagonal shear cracks in the columns close to the beam-column joins. It included cracks at the top of the left column and the bottom of the right column. In
addition, horizontal flexural cracks were predicted along with the middle range of the columns, consistent with the experimental observation.

The standalone OpenSees model predicted a similar pushover curve as the multi-platform model (Fig. 13). However, the frame exhibited a different failure mode. Specifically, the strength after 0.2% drift kept increasing until reaching the peak strength of 501 kN at a drift of 0.36%. The strength degradation after the peak force was not due to the shear failure of the column but attributed to the yielding of the longitudinal rebars.

4 Response history analysis

The application of the proposed multi-platform simulation method to performance assessment of infilled RC frames subjected to ground motions is demonstrated in this section. This study is not aimed at developing a new strut model nor evaluating the performance of existing models, but it suggests improved representation of the RC frame. This includes beam-column joints post-cracking response, shear deformability, and concrete crushing and cracking. This is achieved by using a detailed representation of the frame throughout the multi-platform simulation technique. The validated strut models in Sect. 3 were used here to avoid extra calibration procedures if different test specimens are used (Kirch Nienkotter Rocha et al. 2017; Liberatore et al. 2017; Mohyeddin et al. 2017; Liberatore et al. 2018). Specifically, one is the S1A-2 specimen in Sect. 3.1, which was adopted to represent the infilled RC frames with potential flexural failure of the columns due to earthquake loading. The second specimen S1A-R, on the other hand, was used to represent those with shear-related failure at the frame columns due to the interaction between the RC frame and the infill wall. The S1A-R frame was designed with the same dimensions, materials, and reinforcement details as the S1A-2 specimen, except that the frame columns had a much lower transverse reinforcement ratio, 0.05% compared with 0.14% of specimen S1A-2. The spacing of the columns’ transverse reinforcement was increased from 100 to 280 mm and the diameter of the stirrups remained the same. This reduction was intentionally made to trigger shear-related mechanisms of the columns. The axial load applied to each beam-column joint was accordingly reduced from 200 kN (S1A-2) to 20 kN (S1A-R).

The inertial forces of the two frames were modeled by adding lumped masses to the beam-column joints. As indicated by Huang and Kwon (2015), the numerical model of a RC structure should be able to capture the realistic structural hysteresis, especially for those with a short structural period. Therefore, to show the benefit of the multi-platform simulation method, the lumped masses were specified to obtain a relatively short natural period of the infilled frame, i.e., 0.24 s. It is worth noting that the period was determined from the multi-platform OpenSees-VecTor2 model, and the computed masses were used consistently in the simplified OpenSees model for a fair comparison. Both frames were subjected to the Kobe earthquake ground motion at Fukushima station with scale factors of 5.5 and 4.5 for S1A-2 and S1A-R frames, respectively. The ground motion interval between 5 to 95% of the total Arias intensity is shown in Fig. 15. Rayleigh’s damping was employed with 5% damping ratios for the first and second modes.

Both simplified and multi-platform modeling methods, as presented in Sect. 3.1, were used to investigate the differences between the two methods in simulating the seismic responses of the potential flexure- and shear-critical frames. In structural dynamics, the implicit Newmark method with a nonlinear solution scheme is mostly used to solve the system’s equation of motion (e.g., Newton–Raphson’s method). But in most multi-platform
or hybrid simulations, the non-iterative numerical integration schemes are preferred. This is because the response of the structural component modeled in the substructure module is not only controlled by the final converged displacement but also influenced by the trial displacements from the integration module for nonlinear iterations. Thus, if each time step involves too many iterations and the predicted displacements for the iterations do not increase or decrease monotonically, additional loading cycles will be imposed on the structural component modeled in the substructure module. This will lead to unrealistic cumulative damage and incorrect results Del Carpio et al. (2017). The use of the non-iterative integration schemes is not always suitable for all analysis cases. For example, the non-iterative explicit schemes, such as the Central Difference method and explicit Newmark method, requires the use of a small-time step to ensure their numerical stability. This requirement significantly increases the total number of analysis steps, especially for short period structures like the S1A-2 and S1A-R frames considered in this study. To avoid such a limitation, the non-iterative implicit schemes can be used as they can be unconditionally stable under a certain circumstance. One of the examples is the $\alpha$-Operator Splitting (Alpha-OS) method (Combescure and Pegon 1997), which is unconditionally stable for softening structures when $\alpha$ varies between $-1/3$ and 0. However, as addressed by Del Carpio et al. (2017c), the accuracy of the method depends on the time step, and the method is less accurate for highly nonlinear problems when compared with the implicit Newmark method with a fixed number of iterations using the same time step. To balance the accuracy, stability, and computational efficiency, the implicit method with a fixed number of iterations was used in this study. To avoid the unrealistic cumulative damage of the substructure module (the RC frame model), the minimum number of iterations was defined. A parametric study was carried out and revealed that S1A-2 and S1A-R converged to a solution within two and five iterations per analysis step, respectively. As expected, the shear-critical frame requires additional computational cost. The analysis results are presented and discussed in the following sections.

### 4.1 S1A-2 infilled frame

Figure 16 shows that the lateral deformation histories of the S1A-2 frame predicted from the simplified OpenSees model and the multi-platform OpenSees-VecTor2 model were quite different even at the very beginning of the earthquake. Such difference was

![Kobe earthquake ground motion](image-url)

**Fig. 15** Kobe earthquake ground motion
mainly due to the flexibility of the beam-column joint that was not considered in the simplified OpenSees model as rigid beam-column joints were assumed. The predicted cracks at the beam-column joints in the detailed OpenSees-VecTor2 model are shown in Fig. 17. This figure illustrates the deformed shape and the cracking pattern at the final stage of the multi-platform analysis and it explains the increase of discrepancies between the two models subjected to the ground motion. This comparison implies that models with similar hysteresis curves for a certain predefined loading protocol as shown in Fig. 9 not necessarily ensure consistent time history responses under earthquake excitations. This is an important finding because numerical models for seismic performance assessment were mostly validated through cyclic quasi-static tests. Then, the so-called “validated” models were directly applied to dynamic time history analysis. This simulation approach implies the assumption that the numerical model validated for a certain predefined loading protocol in the quasi-static test can also represent the hysteretic response under earthquake loading. However, the comparison between the simplified and the detailed models reveals that this assumption is not always true.

Fig. 17 Deformed shape and crack pattern of the S1A-2 model (VecTor2 submodel)
To examine the effect of the rigid link elements in the simplified OpenSees model, a new OpenSees model was developed. The rigid link elements were removed in the new model, such as the beams and columns being extended to the joints. Figure 18 compares the OpenSees models with and without the rigid link elements during cyclic quasi-static analysis (similar to Fig. 9). The rigid joint assumption had a minor impact on the hysteretic behavior of the frame due to a predefined displacement history. However, in time history analysis, only the OpenSees model with the flexible beam-column joints was in good agreement with the detailed OpenSees-VecTor2 model, as shown in Fig. 16. Figure 17 shows the deformed shape and frame’s crack pattern at the maximum deflection obtained from the VecTor2 substructure model. Large horizontal cracks were observed at the ends of the two columns. The similar seismic responses shown in Fig. 16 indicate the accuracy of the OpenSees-VecTor2 model and the efficiency of the simplified OpenSees model for modeling flexure-critical infilled RC frames.

4.2 S1A-R infilled frame

The deflection histories of the S1A-R frame are compared in Fig. 19. The simplified OpenSees model without rigid links at the beam-column joints was used here for comparison. It can be seen that the two models predicted similar responses up to 3.255 s, and the hybrid OpenSees-VecTor2 model predicted larger deflections thereafter. This is because of the large shear cracks (maximum shear crack width of 4.25 mm) that developed at the top end of the right column, as shown in Fig. 20a. This response could not be captured by the fiber-section elements in the simplified OpenSees model. In addition to the shear cracks, flexural cracks were developed throughout the columns. After 10 s, the differences between the two responses became more significant. The analysis results reveal that the seismic behavior of the infilled frame could be underestimated if the numerical model fails to capture the considerable shear damage of the frame, particularly for shear-critical elements.

In terms of computing time, it took about 21 h for the multi-platform OpenSees-VecTor2 model to complete the time history analysis of the S1A-R frame. It should be noted...
that this result was based on a time step of 0.005 s for a ground motion of 29.6 s. Also, an implicit integration scheme with five iterations for each analysis step was employed. Computing time could be shortened if a non-iterative integration scheme is used. To further extend the method for system-level assessment of RC infilled frame buildings, the computational efficiency can be significantly improved by only including the critical portions of the frame, such as the shear-critical sections of the beams or columns and the frame joints in the detailed VecTor2 model. The rest may be modeled in the OpenSees model using

![Fig. 19 Lateral deflection history of S1A-R frame](image1)

![Fig. 20 Deformed shape and crack pattern of S1A-R frame at 3.255 s](image2)
simplified elements, such as truss and fiber-section elements. For illustration, a more efficient multi-platform model of the S1A-R frame (referred to as simplified OpenSees-VecTor2 model) was developed, as shown in Fig. 21. Specifically, the columns and upper beam portions between the joint and their connection to the off-diagonal strut were considered critical. Thus, these regions were modeled in the VecTor2 model. Meanwhile, the other portions of the beam and the columns that tended to fail in a flexure manner (Fig. 20a) were modeled with fiber-section elements in OpenSees. In addition, a series of rigid link elements were connected to the interface nodes between the VecTor2 and OpenSees models to account for the inconsistent number of degrees of freedom between the 2D continuum elements in VecTor2 and the fiber-section frame elements in OpenSees. The VecTor 2 model included two translational degrees of freedom per node, while the fiber-section frame elements in OpenSees contained two translational and one rotational degrees of freedom per node.

Figures 22 and 20b show that this simplified OpenSees-VecTor2 model predicted similar deflection histories and failure mode of the critical sections as the original OpenSees-VecTor2 model. The minor difference in the deflection of the frame, as shown in Fig. 22, was mainly due to the use of the rigid link elements, which added extra transverse confinement to the connected beam and columns. In the future study, these rigid link elements can be replaced with more advanced beam-membrane coupling methods, e.g., Sadeghian et al. (2018). Compared with the original OpenSees-VecTor2 model, the simplified multi-platform model almost shortened the computational time by half (i.e., 10 h).

5 Conclusions

A multi-platform simulation approach for infilled RC frames subjected to earthquake excitations is discussed and validated in this paper. The paper shows the ability of the multi-platform models to capture both flexural and shear failures within the RC frame elements. The infill wall is represented by equivalent struts and modeled in OpenSees, while the RC frame is modeled with MCFT-based VecTor2 software using two-dimensional elements.
The comparison of the multi-platform modeling method with the simplified fiber-based modeling method indicates that flexural-critical frames do not require a detailed representation of the frame. Both modeling approaches show good agreement, even when the beam-column joints are slightly cracked. However, this conclusion is based on a simplified fiber-based model where rigid link elements are not used for the beam-column joints. The rigid beam-column assumption typically used in the simplified frame models may underestimate the response under earthquakes, even if the models have been successfully validated against cyclic quasi-static tests.

A detailed model of the frame is crucial for shear-critical frames. These frames were mainly built with inadequate reinforcement detailing before the seismic code became mandatory. The results reveal that the hysteretic behavior of such infilled frame cannot be adequately modeled with fiber-section elements since they fail to capture the significant shear damage of the RC frame. The presented multi-platform simulation provides a solution to overcome this shortcoming. In addition, after properly identifying the critical portions of the structure, such as the beam-column joints and beams/columns within the contact length of the infill walls, the method is applicable to system-level performance assessment of large RC infilled frame structures. For example, two-dimensional continuum elements can be used for the critical components while less detailed elements, such as beam-column elements with distributed or lumped plasticity (Favvata 2008; Karayannis et al. 2011; Burton 2014; Sattar and Liel 2016) can be adopted for the non-critical components. Besides, although the method is demonstrated through infilled RC frames without openings, the proposed multi-platform simulation method is also applicable to infill walls with openings, such as windows and doors. Infilled frames with openings will be analyzed in a similar methodology, and the effect of the opening will be considered through appropriate strut models, e.g., (Kakaletsis and Karayannis 2008, Asteris et al. 2016).

**Acknowledgements** The authors are grateful to Prof. Wei Fan at Hunan university for developing numerical models and running analysis.

**Funding** The authors have not disclosed any funding.
Declarations

Conflict of interest  The authors have not disclosed any competing interests.

References

AASHTO LRFD Bridge Design Specifications (2014) AASHTO LRFD Bridge Design Specifications, seventh edition, American Association of State Highway and Transportation Officials
Agha Beigi H, Sullivan TJ, Christopoulos C, Calvi GM (2015) Factors influencing the repair costs of soft-story RC frame buildings and implications for their seismic retrofit. Eng Struct 101:233–245. https://doi.org/10.1016/J.ENGSTRUT.2015.06.045
Akkaya Y, Guner S, Vecchio FJ (2019) Constitutive model for inelastic buckling behavior of reinforcing bars. ACI Struct J. 116:195–204. https://doi.org/10.14359/51711143
Al-Chaar G (2002) Evaluating strength and stiffness of unreinforced masonry infill structures. Construction Engineering Research Lab. (Army), Champaign, IL. Engineer Research and Development Center
American Society of Civil Engineers (2017a) Seismic Evaluation and Retrofit of Existing Buildings. Standard ASCE/SEI 41–17. American Society of Civil Engineers
Anthoine A (1995) Derivation of the in-plane elastic characteristics of masonry through homogenization theory. Int J Solids Struct 32:137–163. https://doi.org/10.1016/0020-7683(94)00140-R
Asteris PG, Cotovos DM, Chrysostomou CZ et al (2013) Mathematical micromodeling of infilled frames: State of the art. Eng Struct 56:1905–1921. https://doi.org/10.1016/j.engstruct.2013.08.010
Asteris PG, Cavaleri L, Di Trapani F, Sarhosis V (2016) A macro-modelling approach for the analysis of infilled frame structures considering the effects of openings and vertical loads. Struct Infrastruct Eng 12:551–566. https://doi.org/10.1080/15732479.2015.1030761
Bentz EC (2005) Explaining the riddle of tension stiffening models for shear panel experiments. J Struct Eng 131:1422–1425. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:9(1422)
Bentz EC, Vecchio FJ, Collins MP (2006) Simplified modified compression field theory for calculating shear strength of reinforced concrete elements. ACI Struct J 103:614–624
Bertoldi SH, Decanini LD, Gavarini C (1993) Telai tamponati soggetti ad azioni sismiche, un modello semplificato: confronto sperimentale e numerico. Atti del 6.Oct:815–824
Brodsky A (2021) A micro – macro modelling methodology for the analysis of infilled frames. Bull Earthq Eng 19:2161–2184. https://doi.org/10.1007/s10518-021-01045-9
Brodsky A, Huang X (2021) Multi-platform modelling of masonry infilled frames. J Build Eng. 1:15
Brodsky A, Rabinowitch O, Yankelevsky DZ (2018) Determination of the interaction between a masonry wall and a confining frame. Eng Struct 167:214–226. https://doi.org/10.1016/j.engstruct.2018.04.001
Burton H, Deierlein G (2014) Simulation of seismic collapse in nonductile reinforced concrete frame buildings with masonry infills. ASCE J Struct Eng. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000921
Canadian Standards Association (2014c) CSA A23.3 : 2014 DESIGN OF CONCRETE STRUCTURES
Cavaleri L, Papia M (2003) A new dynamic identification technique: application to the evaluation of the equivalent strut for infilled frames. Eng Struct 25:889–901. https://doi.org/10.1016/S0141-0296(03)00023-3
Cavaleri L, Di Trapani F (2014) Cyclic response of masonry infilled RC frames: experimental results and simplified modeling. Soil Dyn Earthq Eng 65:224–242. https://doi.org/10.1016/j.soildyn.2014.06.016
Chrysostomou CZ, Gergely P, Abel JF (2002) A six-strut model for nonlinear dynamic analysis of steel infilled frames. Int J Struct Stab Dyn 02:335–353. https://doi.org/10.1142/s0219455402000567
Combescure D, Pegon P (1997) α-operator splitting time integration technique for pseudodynamic testing error propagation analysis. Soil Dyn Earthq Eng 16:427–443. https://doi.org/10.1016/S0267-7261(97)00017-1
Del Carpio M, Hashemi MJ, Mosqueda G (2017) Evaluation of integration methods for hybrid simulation of complex structural systems through collapse. Earthq Eng Eng Vib 16:745–759. https://doi.org/10.1007/s11803-017-0411-z

Di Trapani F, Cavalieri L (2015) Masonry infills and RC frames interaction: literature overview and state of the art of macromodeling approach. Eur J Environ Civ Eng. https://doi.org/10.1080/19648189.2014.996671

Di Trapani F, Tomaselli G, Cavalieri L, Bertagnoli G (2021) Macromodel Element for the Progressive-Collapse Analysis of Infilled Frames. J Struct Eng 147:04021079. https://doi.org/10.1061/(asce)st.1943-541x.0003014

Fierro E (2001) Initial Report on 23 June 2001 Atico, Peru Earthquake - Part II. EERI Spec Earthq Rep 1–10

Eligehausen R, Popov EP, Bertero VV (1982) Local bond stress-slip relationships of deformed bars under generalized excitations. University of California, Berkeley

Elwood KJ (2004) Modelling failures in existing reinforced concrete columns. Can J Civ Eng 31(5):846–859

Erdem MM, Emsen E, Bijke M (2021) Experimental and numerical investigation of new flexible connection elements between infill walls-RC frames. Constr Build Mater 296:123605. https://doi.org/10.1016/j.conbuildmat.2021.123605

Favvata MJ, Izzuddin BA, Karayannis CG et al (2008) Modelling exterior beam–column joints for seismic analysis of RC frame structures. Earthq Eng Struct Dyn 37:1527–1548. https://doi.org/10.1002/EQE.826

FEMA 306: Applied Technology Council, Partnership for Response (1999) FEMA 306: Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings: Basic Procedures Manual. The Agency

Feng Y, Wu X, Zhang S (2014) Failure modes of masonry infill walls and influence on RC frame structure under earthquake. In: NCEE 2014 - 10th U.S. national conference on earthquake engineering: frontiers of earthquake engineering

Fierro E (2007) Learning from earthquakes: The Pisco, Peru, earthquake of August 15, 2007

Gao X, Stavridis A, Bolis V, Preti M (2018) Experimental study on the seismic performance of non ductile RC frames infilled with sliding subpannels. Integr Sci Eng Policy 6:3927–3937

Ghannoun WM, Moehle JP (2012) Dynamic collapse analysis of a concrete frame sustaining column axial failures. ACI Struct J. 109:403–412. https://doi.org/10.14359/51683754

Grande E, Imbimbo M, Napoli A et al (2021) A macro-modelling approach for RC beam-column exterior joints: first results on monotonic behaviour. J Build Eng 39:102202. https://doi.org/10.1016/J.JOBE.2021.102202

Haldar P, Singh Y, Paul DKK (2013) Identification of seismic failure modes of URM infilled RC frame buildings. Eng Fail Anal 33:97–118. https://doi.org/10.1016/j.engfailanal.2013.04.017

Hareen CBV, Mohan SC (2021) Evaluation of seismic torsional response of ductile RC buildings with soft first story. Structures 29:1640–1654. https://doi.org/10.1016/j.istruc.2020.12.031

He XG, Kwan AKH (2001) Modeling dowel action of reinforcement bars for finite element analysis of concrete structures. Comput Struct 79:595–604. https://doi.org/10.1016/S0045-7949(00)00158-9

Huang X, Kwon OS (2015) Numerical models of RC elements and their impact on seismic performance assessment. Earthq Eng Struct Dyn 44:283–298

Huang X, Kwon OS (2020) A generalized numerical/experimental distributed simulation framework. J Earthq Eng 24:682–703

Huang H, Burton HV, Sattar S (2020) Development and utilization of a database of infilled frame experiments for numerical modeling. J Struct Eng 146:04020079. https://doi.org/10.1061/(asce)st.1943-541x.0002608

Ibarra LF, Medina RA, Krawinkler H (2005) Hysteretic models that incorporate strength and stiffness deterioration. Earthq Eng Struct Dyn 34:1489–1511. https://doi.org/10.1002/eqe.495

Kakaletis DJ, Karayannis CG (2008) Influence of masonry strength and openings on infilled R/C frames under cycling loading. J Earthq Eng 12:197–221. https://doi.org/10.1080/13632460701299138

Karayannis CG, Favvata MJ, Kakaletis DJ (2011) Seismic behaviour of infilled and pilotis RC frame structures with beam–column joint degradation effect. Eng Struct 33:2821–2831. https://doi.org/10.1016/J.ENGSTRUCT.2011.06.006

Karmacharya U, Silva V, Brzev S, Martins L (2018) Improving the Nepalese building code based on lessons learned from the 2015 M7.8 Gorkha earthquake. Elsevier Inc., Amsterdam

Kawa M, Pietruszczak S, Shieh-Beygi B (2008) Limit states for brick masonry based on homogenization approach. Int J Solids Struct 45:998–1016. https://doi.org/10.1016/j.ijsolstr.2007.09.015

Kirch Nienkotter Rocha B, Mohyeddin A, Lumantarna E, Kumar Shukla S (2017) Sensitivity of the Strut Model for an RC Infill-Frame to the Variations in the Infill Material Properties Dynamic analysis of soil slope View project. In: Australian Earthquake Engineering Society Conference
Kupfer H, Hilsdorf HK, Rusch H (1969) Behavior of concrete under biaxial stresses. J Proc 66:656–666

Liberatore L et al (2017) Comparative assessment of strut models for the modelling of in-plane seismic response of infill walls. In: Proceedings of the 6th international conference on computational methods in structural dynamics and earthquake engineering (COMPDYN), Rhodes, Greece

Liberatore L, Noto F, Mollaioi F, Franchin P (2018) In-plane response of masonry infill walls: Comprehensive experimentally-based equivalent strut model for deterministic and probabilistic analysis. Eng Struct 167:533–548. https://doi.org/10.1016/j.engstruct.2018.04.057

Liel AB, Asce M, Haselton CB et al (2010) Seismic collapse safety of reinforced concrete buildings. II: comparative assessment of nonductile and ductile moment frames. J Struct Eng 137:492–502. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000275

Lu X, Yang Z, Chea C, Guan H (2020) Experimental study on earthquake-induced falling debris of exterior infill walls and its impact to pedestrian evacuation. Int J Disaster Risk Reduct 43:101372. https://doi.org/10.1016/J.IJDRR.2019.101372

Mainstone RJ (1971) On the stiffness and strengths of infilled frames. Proc Inst Civ Eng. https://doi.org/10.1680/jicep.1971.6267

Mander JB, Priestley MJN, Park R (1989) Theoretical stress-strain model for confined concrete. ASCE J Struct Eng 114:1804–1826

McKenna F (2011) OpenSees: A framework for earthquake engineering simulation. Comput Sci Eng 13:58–66. https://doi.org/10.1109/MCSE.2011.66

Mohyeddin A, Dorji S, Gad EF, Goldsworthy HM (2017) Inherent limitations and alternative to conventional equivalent strut models for masonry infill-frames. Eng Struct 141:666–675. https://doi.org/10.1016/J.ENGSTRUCT.2017.03.061

Montoya E, Vecchio FJ, Sheikh SA (2006) Compression field modeling of confined concrete: constitutive models. J Mater Civ Eng 18:510–517. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:4(510)

Mortazavi P, Huang X, Kwon O-S, Christopoulos C (2017) Example manual for the University of Toronto simulation framework. an open-source framework for integrated multiplatform simulations for structural resilience. Technical Report, Department of Civil and Mineral Engineering, University of Toronto, Toronto, Canada

Motovali Emami SM, Mohammadi M, Lourenço PB (2017) Equivalent diagonal strut method for masonry walls in pinned connection and multi-bay steel frames. J Seismol Earthq Eng 49(19):299

Noh NM, Liberatore L, Mollaioi F, Tesfamariam S (2017) Modelling of masonry infilled RC frames subjected to cyclic loads: state of the art review and modelling with OpenSees. Eng Struct 150:599–621. https://doi.org/10.1016/j.engstruct.2017.07.002

Palermo D, Vecchio FJ (2007) Simulation of cyclically loaded concrete structures based on the finite-element method. J Struct Eng ASCE 133:728–738

Papia M, Cavaleri L, Fossetti M (2003) Infilled frames: developments in the evaluation of the stiffening effect of infills. Struct Eng Mech 16:675–693. https://doi.org/10.12998/sem.2003.16.6.675

Park R, Priestley MJN, Gill WD (1982) Ductility of square-confined concrete columns. J Struct Div 108:929–950

Pasca M, Liberatore L, Masiani R (2017) Reliability of analytical models for the prediction of out-of-plane capacity of masonry infills Masonry infilled frames View project Seismic behaviour of masonry buildings View project. Struct Eng Mech 64:765–781. https://doi.org/10.12989/sem.2017.64.6.765

Paulay T, Priestly MJN (1992) Seismic design of reinforced concrete and masonry buildings. John Wiley & Sons Inc, Hoboken

Richart FE, Brandtsaeg A, Brown RL (1928) A study of the failure of concrete under combined compressive stresses. Eng Exp Stn 185(26):7–92

Sadeghian V, Kwon OS, Vecchio F (2018) Modeling beam-membrane interface in reinforced concrete frames. ACI Struct J 115:825–836

Sattar S, Liel AB (2016) Seismic performance of nonductile reinforced concrete frames in-plane infill walls - I: development of a strut model enhanced by finite element models. Earthq Spectra 32:795–818. https://doi.org/10.1177/0748756516646594

Sezen H, Moehle JP (2004) Shear strength model for lightly reinforced concrete columns. J Struct Eng 130:1692–1703. https://doi.org/10.1061/(ASCE)0733-9445(2004)130:11(1692)

Sezen H, Whittaker AS, Elwood KJ, Mosalam KM (2003) Performance of reinforced concrete buildings during the August 17, 1999 Kocaeli, Turkey earthquake, and seismic design and construction practice in Turkey. Eng Struct 25:103–114. https://doi.org/10.1016/S0141-0296(02)00121-9

Suzuki T, Puranam AY, Elwood KJ et al (2021) Shake table tests of seven-story reinforced concrete structures with torsional irregularities: test program and datasets. Earthq Spectra 37:2946–2970. https://doi.org/10.1177/87552930211016869
Uva G, Raffaele D, Porco F, Fiore A (2012) On the role of equivalent strut models in the seismic assessment of infilled RC buildings. Eng Struct 42:83–94. https://doi.org/10.1016/j.engstruct.2012.04.005

Vecchio F (1982) The response of reinforced concrete to in-plane shear and normal stresses. Publication 82

Vecchio FJ (1992) Finite element modeling of concrete expansion and confinement. J Struct Eng 118:2390–2406. https://doi.org/10.1061/(asce)0733-9445(1992)118:9(2390)

Vecchio FJ, Collins MP (1986) The modified compression-field theory for reinforced concrete elements subjected to shear. ACI J 83:219–231

Vecchio FJ, Shim W (2004) Experimental and analytical reexamination of classic concrete beam test. J Struct Eng ASCE 130:460–469

Verderame GM, Ricci P, De Risi MT, Del Gaudio C (2019) Experimental assessment and numerical modeling of conforming and non-conforming RC frames with and without infills. J Earthq Eng. https://doi.org/10.1080/13632469.2019.1692098

Walraven JC (1981) Fundamental analysis of aggregate interlock. J Struct Div 107:2245–2270

Wararucksajja W, Srechai J, Leelataviwat S (2020) Seismic design of RC moment-resisting frames with concrete block infill walls considering local infill-frame interactions. Bull Earthq Eng 18:6445–6474. https://doi.org/10.1007/s10518-020-00942-9

Wijaya H, Rajeev P, Gad E, Amirsardari A (2020) Effect of infill-wall material types and modeling techniques on the seismic response of reinforced concrete buildings. ASCE Natrual Hazards Rev 21:04020031

Wong PS, Vecchio FJ, Trommel H (2013) Vector2 & formworks user’s manual second edition

Yassin MHM (1994) Nonlinear analysis of prestressed concrete structures under monotonic and cyclic loads. University of California, Berkeley

Zucchini A, Lourenço PB (2009) A micro-mechanical homogenisation model for masonry: application to shear walls. Int J Solids Struct 46:871–886. https://doi.org/10.1016/j.ijsolstr.2008.09.034

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.