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Modelling failure analysis of RC frame structures with masonry infills under sudden column losses

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Abstract

Robustness of structures is fundamental to limit progressive collapse of buildings in case of accidental loss of columns due to explosions, impacts or materials deterioration. Modelling of progressive collapse response of reinforced concrete (RC) frame structures needs considering extreme geometric and mechanical nonlinearities. Moreover, in the case of infilled frames the collapse mechanism becomes more complex because of the frame-infill interaction. This paper presents a numerical study aimed at proposing: a) an appropriate fiber-section modeling methodology for reinforced concrete frames under large displacement progressive collapse events; b) a new multi-strut fiber macro-element model to account for the influence of masonry infills in the progressive collapse response. Proposed numerical models are developed using the *OpenSees* software platform. The predictive capacity of the proposed methodology is widely validated in the paper through comparisons with experimental test results and refined numerical simulation pushdown test results. Results show that the new equivalent-strut modeling approach can be suitably employed as a simple assessment method when numerical simulation of progressive collapse scenarios is needed for bare and infilled reinforced concrete frames.

Keywords: Progressive collapse; pushdown; robustness; infills; reinforced concrete.

1. Introduction

In the last years, the interest in structural robustness and progressive collapse analysis of constructions is rapidly growing within the scientific community and in practice engineering. For civil structures having residential, commercial

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or public use, the possibility of limiting damage progression due to the accidental loss of a primary structural element, such as a column, becomes essential to avoid disproportionate consequences. In fact, robustness based design of buildings addresses solutions avoiding that damage suffered by a structure, due to an accidental event, would not be disproportionate with respect to the cause that generated it, and as many times recognized in the past. In frame structures, the loss of a perimetral column due to impacts, explosions or advanced material degradation configures problem of the structure response, hence, the assessment of damage propagation opens different potential scenarios.

For reinforced concrete structures, the possibility of avoiding or limiting multiple collapses as a consequence of a column loss depends on the capacity of the beams converging to the removed column, to switch from the initial flexural resistant mechanism combined with the arching action, to a subsequent catenary mechanism, under large displacements regime. Effective development of the catenary mechanism is related to a number of factors but basically depends on the ductility of the plasticized cross-sections along with the residual strength and deformation capacity of materials when the catenary mechanism is initiated.

In recent years, several authors have carried out studies regarding the assessment of the robustness of frame structures subject to accidental losses from a theoretical/numerical (Izzuddin et. al., 2008, Vlassis et al, 2008) and experimental point of view (Weng et. al. 2017, Pham et al., 2017, Lew et al. 2011) associated with numerical interpretations. The main results refer that the deformation capacity of beam end cross-sections plays a fundamental role on the activation capacity of the catenary mechanism, but also that this is conditioned by further factors such as the horizontal constraint degree as well as the real capacity of elongation of steel. A further issue is related to the influence of masonry infills within the progressive collapse scenario. In fact infills strongly interact with reinforced concrete frames even in case of vertical actions, modifying the response with an increase of strength and stiffness and reduction deformation capacity (Quian and Li, 2017, Li et al., 2019, Di Trapani et al., 2020).

As it can be easily understood from the previous background, the determination of progressive collapse response of buildings requires refined analyses and models able to capture the very advanced damage state response of materials as well as locales ruptures (Fig. 1). Based on the results of a number of experimental tests, this paper shows a framework to efficiently perform modelling of progressive collapse of RC structures using OpenSees and the necessary expedients to include in order accounting for specific damage phenomena. Further, a fiber section macro-element modelling approach is proposed to consider the presence of infills. Even in this case validation of the model is supported by a comparison with the results of experimental tests.

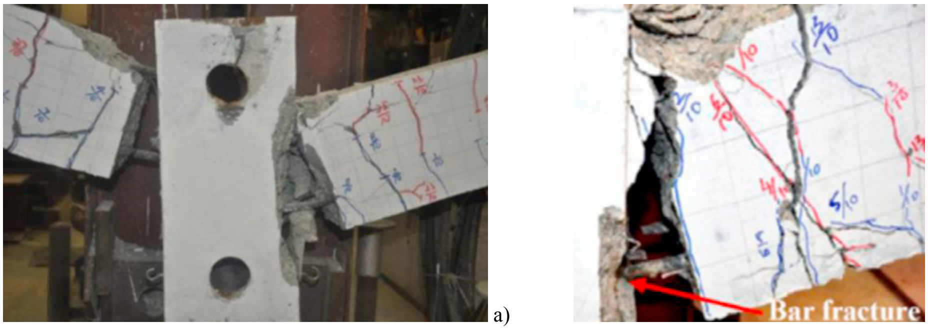


Fig. 1. Final stage of progressive collapse tests on beams by: a) [3]; b) [4].

2. Modelling of progressive collapse response of RC elements

2.1. Specimens details and modelling approach

All the aforementioned (and others) experimental pushdown tests carried out on beam systems and frames highlighted following recurring stages for the investigated systems: a) flexural mechanism and cracking at the beam ends; b) arching mechanism with strong increase of axial compressive force on beams and horizontal thrust toward the outer columns; c) yielding of rebars in tension and buckling in compression; d) rupture of bottom rebars and activation of double cantilever mechanism; e) initiation of the catenary mechanism (axial force switches from compression to tension); f) large displacement stage with regain of strength up to the rupture of top rebars causing equilibrium loss.

In order to define a benchmark modelling approach, different experimental pushdown tests have been simulated in OpenSees adopting the modelling choices described in the following. Specimens testes are those by Weng et al. (2017), Pham et al. (2019), Lew et al. (2011). Design details of the specimens are illustrated in Fig. 2, while reference material properties are listed in Table 1.

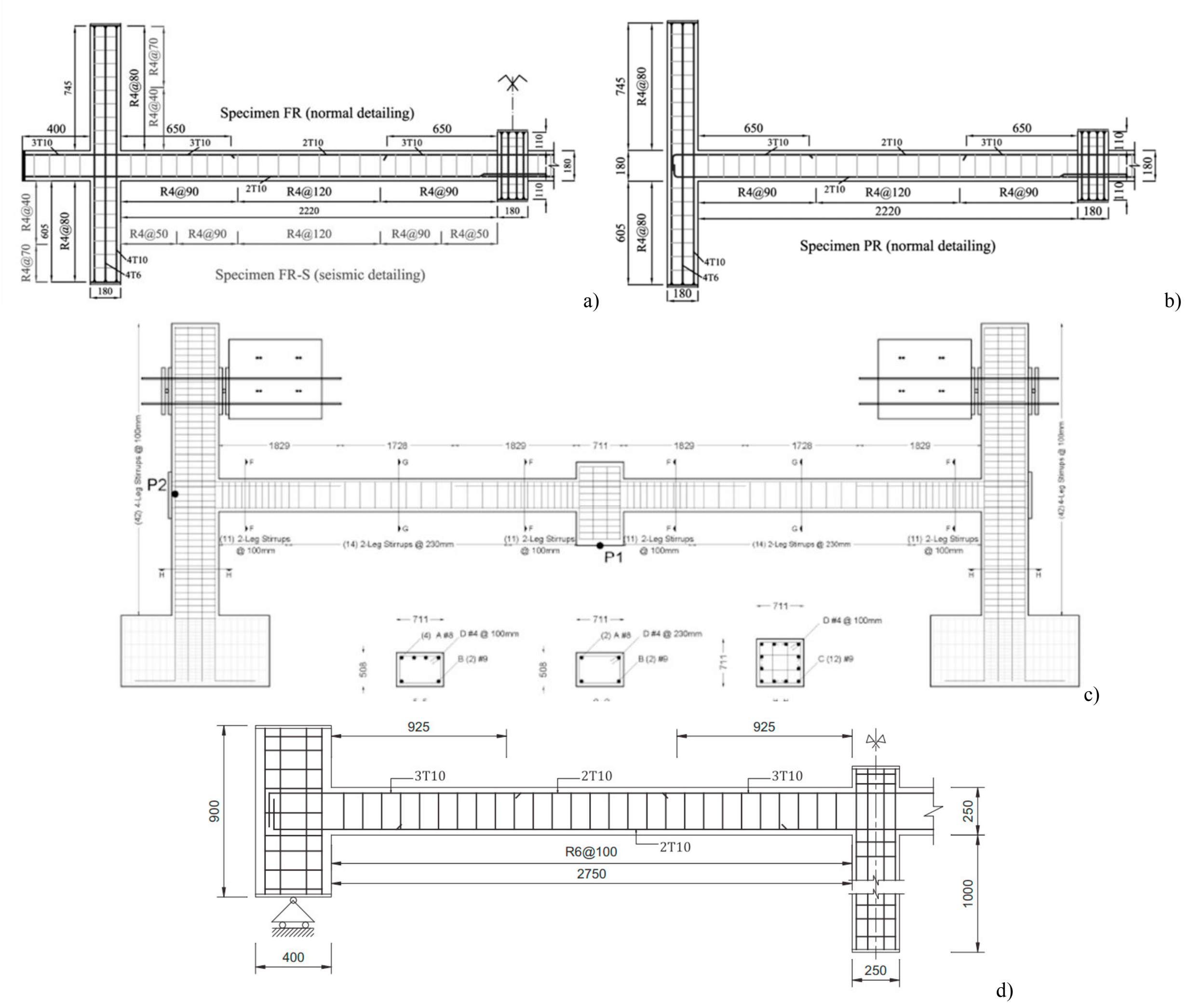


Fig. 2. Design details of specimens by: (a) Weng et al. 2017 (FRS), (b) Weng et al. 2017 (PR), (c) Lew et al. 2011, (d) Pham et al. (2017)

Reinforced concrete elements are modeled by displacement based fiber-section beam-column elements. A proper mesh refinement at the ends of the beams is performed in order to allow an adequate prediction of curvatures distribution along the beam length. Moreover, beam elements are also differentiated in order to take into account confinement action due to the different stirrup spacing. The element fiber cross-sections are defined using the Concrete 02 model (Fig 3) specifically calibrated to consider the different confinement action. Special care is also addressed to model steel rebars behaviour in tension, in order to detect a tensile fracture, and compression, to account for buckling. The non-symmetric behaviour of steel is assigned by the Hysteretic material model with elasto-plastic behaviour up to the achievement of the ultimate strain ε_{su} in tension and a softening branch in compression whose slope is determined following the rules by the Dakhal and Maekawa (2002) post yielding buckling model (Fig 3).

Table 1. Material properties of specimens.

Specimen	Unconfined concrete compressive strength f_c (MPa)	Concrete tensile strength f_t (MPa)	Steel yielding strength f_{sy} (MPa)	Steel ultimate strength f_{st} (MPa)	Steel ultimate strain ε_{su} (-)
Weng et al. (2017) (FR)	30.0	2.0	505	605	0.14
Weng et al. (2017) (FR-S)	30.0	2.0	505	605	0.14
Weng et al. (2017) (PR)	30.0	2.0	505	605	0.15
Lew et al. (2011)	32.0	3.1	470	650	0.25
Pham et al. (2017)	39.0	3.5	500	600	0.20

Beam-column intersections in correspondence of the joints are modeled as rigid links. Specimens by Weng et al. (2017) and Pham et al. (2019) have been tested using elastic horizontal elastic constraints having fixed stiffness. The latter are modeled as elastic springs having the same stiffness as that declared by authors. Corotational coordinate transformation if finally used to consider geometric non-linearity under large displacement stages.

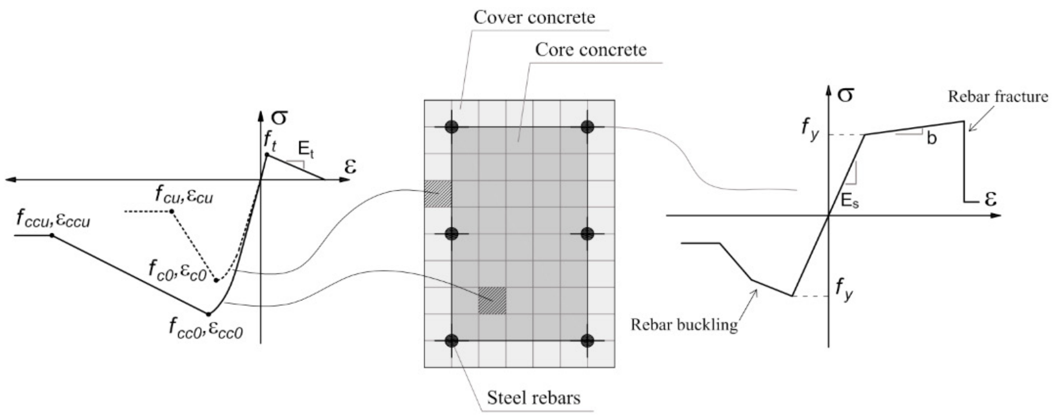


Fig. 3. Fiber cross-section assembly and materials stress-strain laws.

2.2. Validation tests

Experimental pushdown tests of the specimens have been simulated in OpenSees. A sample of the arrangement of an OpenSees model (specimen by Pham et al. (2019)) for the simulation of pushdown tests is shown in Fig. 4. Comparisons vertical-force/vertical displacement responses are illustrated in Fig. 5. From the results, it can be observed that the proposed modelling framework resulted sufficiently reliable in predicting the experimental responses of specimens, despite the large geometrical and mechanical nonlinearity. In particular, it was possible to identify with good accuracy the sequence of ruptures of rebars as well as the hardening behaviour due to the activation of the catenary mechanism.

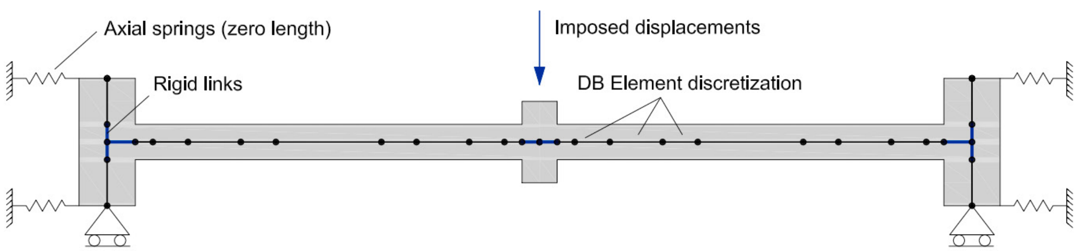


Fig. 4. Sample of the arrangement of the OpenSEES model to simulate experimental pushdown tests (Specimen by Pham et al, 2019).

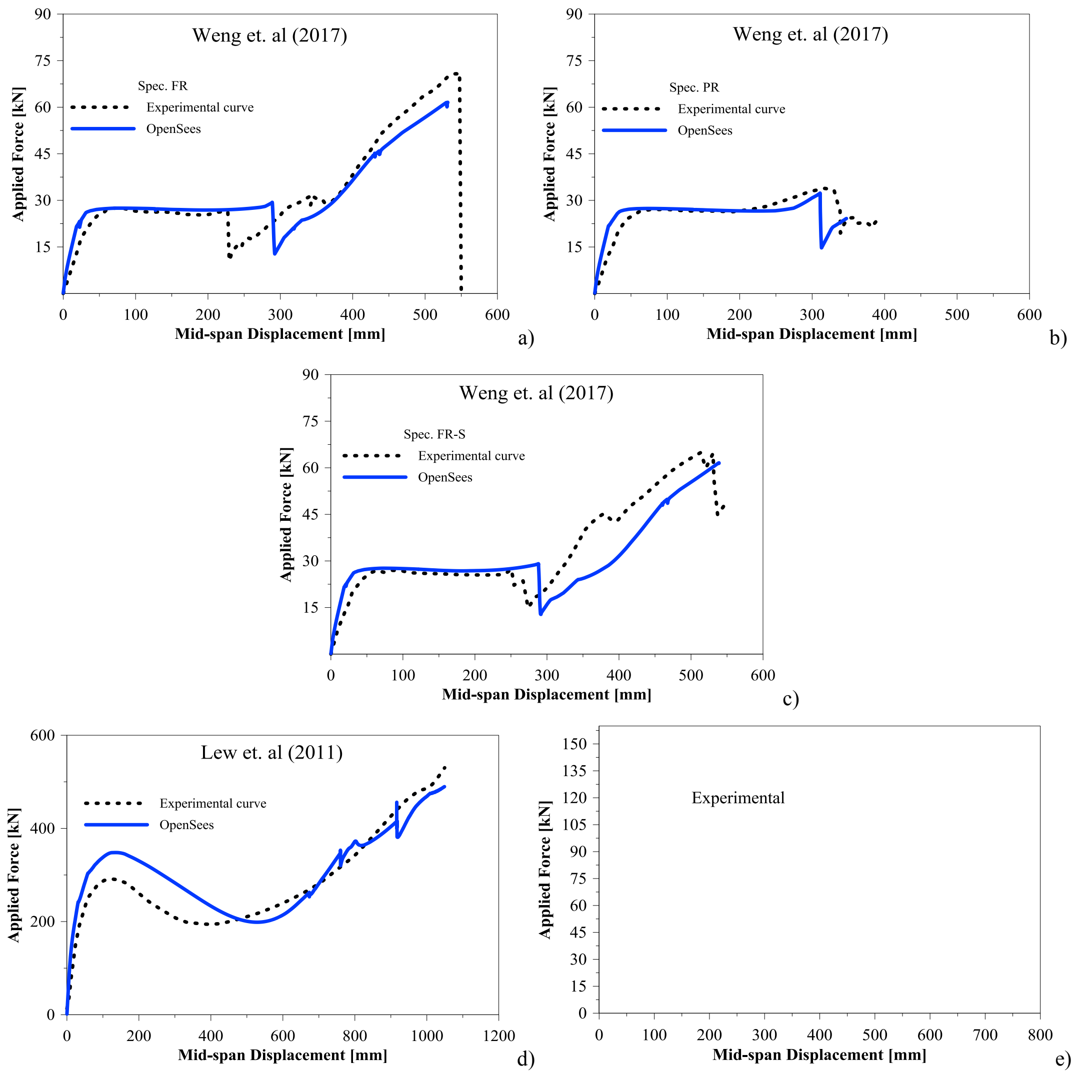


Fig. 5. Experimental results compared with numerical predictions by the OpenSees fiber-section mode: (a) Weng et al. (2017) - Spec. FR; (b) Weng et al. (2017) - Spec. PR; (c) Weng et al. (2017) - Spec. FR-S; (d) Lew et al. (2011); (e) Pham et al. (2011).

3. Modelling of progressive collapse response of infilled frames

3.1. Pushdown response of an infilled frame and simplified modelling proposal

Experimental and numerical investigations carried out on infilled frames subject to pushdown tests (Quian and Li, 2017, Li et al., 2019, Di Trapani et al., 2020) have highlighted a substantial modification of the pushdown response with respect to the bare frames. In detail, the presence of the infills results in an overall increase of strength and stiffness associated with a lower ductility. Some of the numerical specimens and test results carried out by Di Trapani et. al (2020) are shown in Figs. 6, 7. The damage pattern in Figs. 6b, 7b highlight the formation of two compression fields in the masonry, which induce the migration of the plastic hinges toward the inner of the beams. Sliding and detachment of mortar joints is also observed in the in order to find a computationally effective modelling strategy to simulate progressive collapse response, a possible adaption of equivalent strut modelling approach is here tested, while acknowledging that: a) load direction in case of column loss is vertical instead of horizontal; b) observed collapse mechanisms are different from those typical of infilled frames subjected to seismic actions.

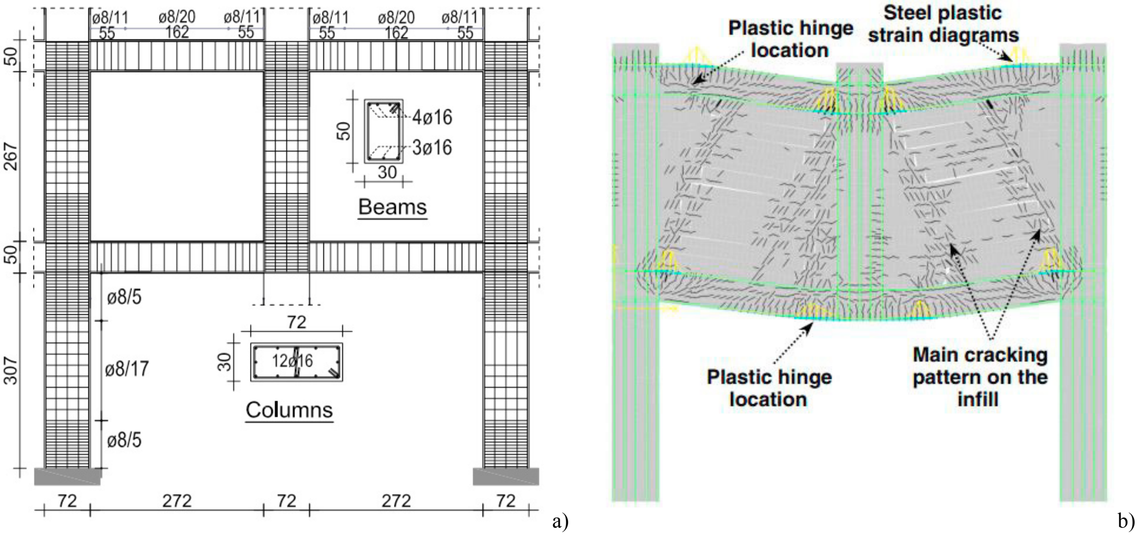


Fig. 6. Numerical specimen with l_b/h_c=1 by Di Trapani et. al 2020: (a) Geometric details; (b) Damage pattern at the end of the simulation.

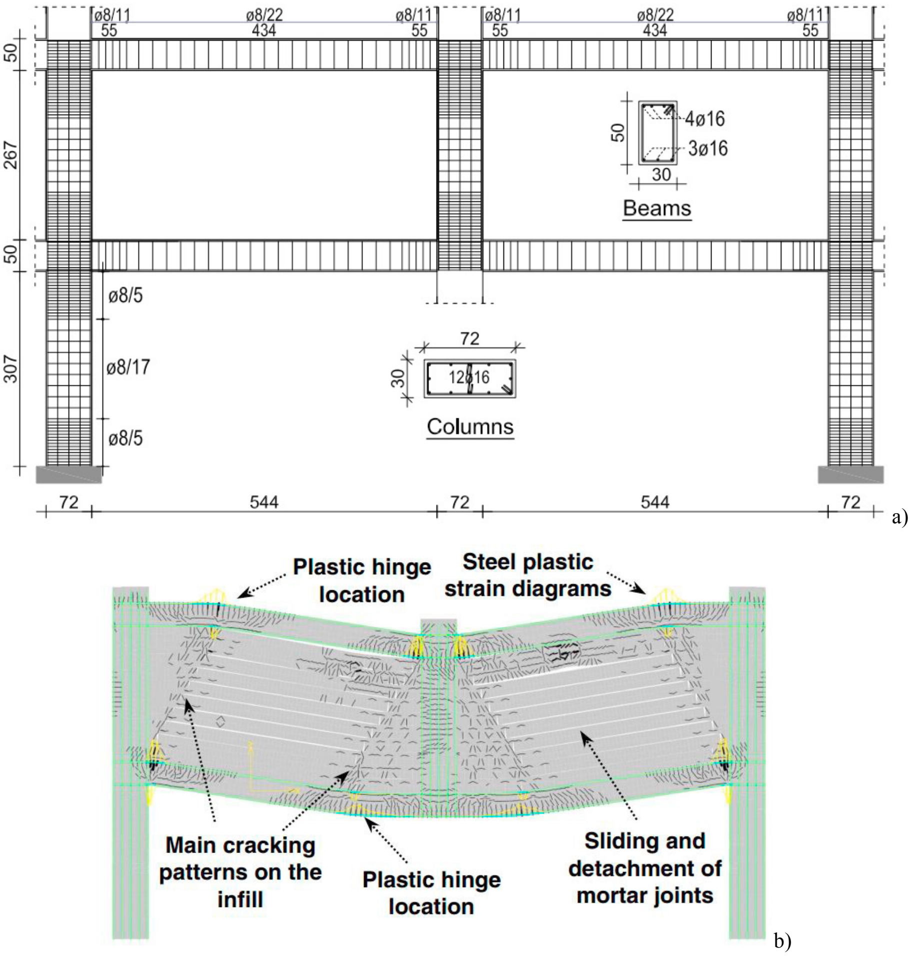


Fig. 7. Numerical specimen with l_b/h_c=2 by Di Trapani et. al 2020: (a) Geometric details; (b) Damage pattern at the end of the simulation.

Numerical tests previously shown are reproduced with OpenSees considering using a fiber-section approach to model beams and columns, and an equivalent 3-strut model to reproduce infills. The proposed equivalent 3-strut model is conceived as an adaption of the single equivalent-strut model by Di Trapani et al. (2018). The original approach is modified by the 3-strut configuration shown in Fig. 8, in which S1 struts have the same configuration as in the original model, while for the determination of stress-strain and geometric parameters of the strut, the expression provided by Di Trapani et al. (2018) are used inverting the length of the infill (l_b) with its height (h_c). In the 3-strut configuration, S1 strut is accompanied by two rigid struts (S2 struts) which start from the end of S1 strut and point toward the top and bottom beams at a distance αl_b (Fig. 8). S2 struts are included in the model to simulate in a more effective way the observed damage mechanism, in which, masonry at corners remains almost intact. The distance αl_b represents the position where the plastic hinge forms. From the damage patterns observed by the FE models pushdown tests, it can be reasonably assumed that assumed αl_b =0.20 l_b in the case in which l_b / h_c =1 and αl_b =0.35 l_b if l_b/h_c =2. The tests are carried out for four specimens among those previously tested, in detail these are seismically designed frames with and without lateral constraints and with square and rectangular aspect ratio (l_b/h_c =1 and l_b/h_c =2). Results of comparisons are illustrated in Figs. 9a and 9b and confirm the good predictive capacity of the model despite the simplicity of its definition. Deformed shapes shown in Fig. 10 also demonstrate the consistency with experimental and numerical tests.

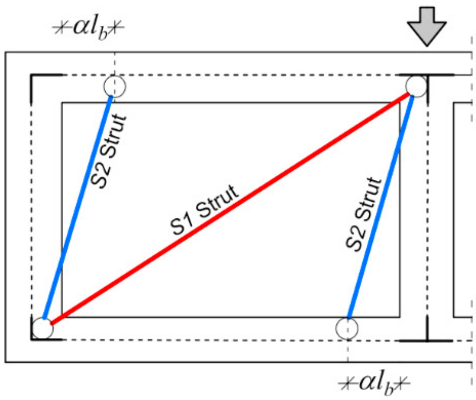


Fig. 8. Proposed 3-strut macro-modelling approach.

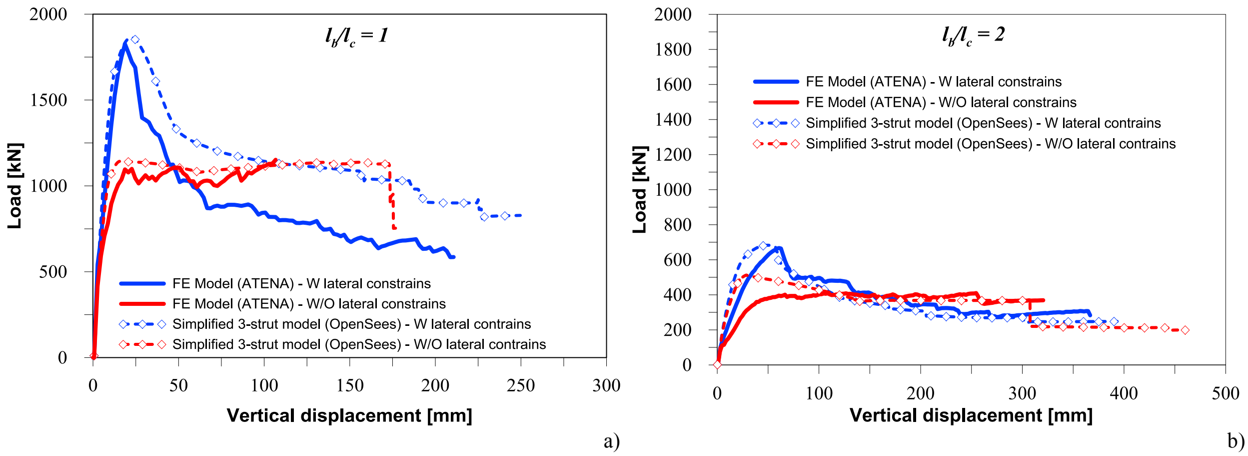
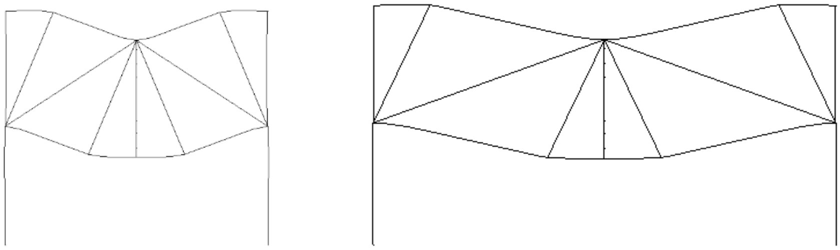


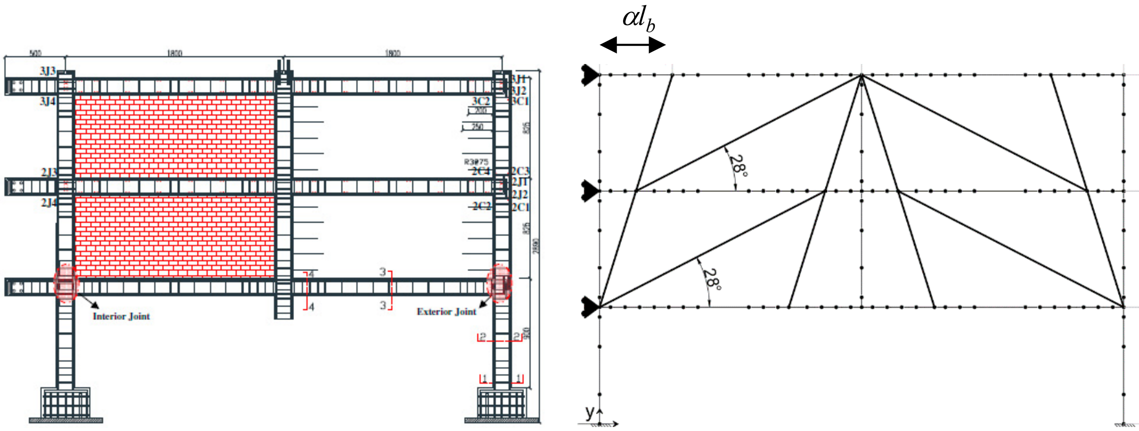
Fig. 9. Refined FE model results by Di Trapani et al. (2020) compared with numerical predictions by the 3-strut OpenSees model: (a) Specimens with *l*/*h*=1; (b) Specimens with *l*/*h*=2.

A further validation test of the proposed modelling approach is carried out against results from the infilled frame specimens by Quian et al. (2017). The latter are 2-storey brick infilled frames designed with and without seismic details. The specimens are restrained only from one side. A sample of one specimen is shown in Fig. 11a. The associated 3-strut OpenSees model is also reported in Fig. 11b. In this case, the S2 struts are continuous from the first to the top storey beam. The distance αl_b ($0.35\ l_b$) is first assigned at the top-beam, defining a consequent linear dependence for the definition of connection joints at the bottom beams. Experimental results of the two specimens are compared with numerical predictions by the proposed model (Fig. 12). Even in this case results confirm the reliability of the proposed model in predicting pushdown resistance and post-peak response.



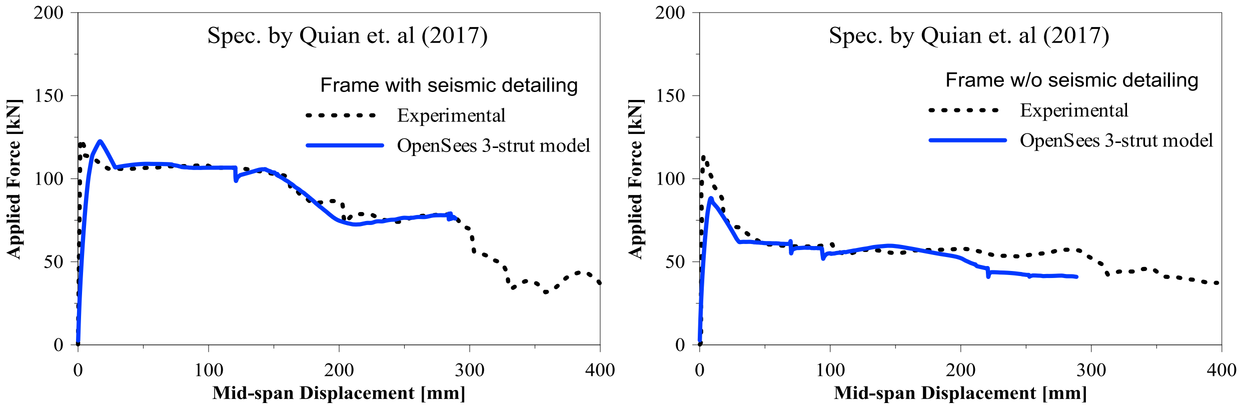
a) b)

Fig. 10. Deformed shapes by the 3-strut infilled frame models: a) Specimens with l/h=1; b) Specimens with l/h=2.



a) b)

Fig. 11. Specimens by Quian et al. (2017): (a) Specimen without seismic detailing; (b) 3- Strut OpenSees model.



a) b)

Fig.12. Experimental tests by Quian et al. (2017) compared with numerical predictions by the proposed 3-strut model: (a) Specimens with seismic detailing; (b) Specimens without seismic detailing.

4. Conclusions

The paper has shown a framework to efficiently perform modelling of progressive collapse of RC structures using OpenSEES and the necessary expedients to consider in order to account for specific damage phenomena occurring under large displacement configurations (e.g. catenary mechanism, rebars bucking and rebars fracture). Moreover, a 3-strut macro model simulating the influence of infill within RC frame has been also proposed and validated against experimental and refined numerical tests. Results have shown the suitability of the proposed fiber-section multi-strut approach and its reliability in predicting the response of bare and infilled frame system subject to progressive collapse.

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