1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.105

Macromodel of RC frame with masonry infill for detailed assessment of structural performance

Amar Kadić[1], Senad Medić[2], Davorin Penava[3]

[1] *Mag.ing.aedif.*, INFRA Ltd, *amar.kadic@infra.ba*

[2] *Assistant Professor*, Faculty of Civil Engineering, University of Sarajevo, *senad_medic@yahoo.com*

[3] *Associate Professor*, Josip Juraj Strossmayer University of Osijek, *davorin.penava@gfos.hr*

Abstract

Infill walls significantly affect the resistance of structure. However, in the design it is generally neglected which leads to erroneous assessment of stiffness, load bearing capacity and serviceability. Seismic response of reinforced concrete frames with masonry infill can be analysed employing models of different complexity: micro-, meso- and macromodels. Macromodelling strategy, where masonry infill is represented by homogenized orthotropic continuum, requires low computational effort and basic material information without losing accuracy of global structural behaviour. Highly nonlinear behaviour of RC frame and masonry infill as well as their mutual interaction was modelled using quadratic membrane elements in DIANA FEA. Total strain rotating crack constitutive model was used for concrete, von Mises for embedded rebars and engineering masonry model for hollow infill. Mohr-Coulomb contact elements with gapping, applied at the interface between frame and infill, had significant influence on the structural response. The sensitive interface properties were calibrated after experimental tests which included masonry infilled frame with and without opening as well as bare frame. In order to match the response of the model and the experiment, it was necessary to model friction between rollers and the columns using bilinear springs. Cyclic static loading was imposed on the structure under constant vertical precompression. Failure modes pertain to crushing of infill corners and gradual separation of brittle masonry from the frame which further leads to formation of diagonal strut. The development of damage in the reinforced concrete frame and masonry infill according to the EMS-98 scale is described and recommendations for numerical modelling are given.

Key words: macromodel, reinforced concrete frame, masonry infill, DIANA FEA, experimental testing

1 Introduction

Reinforced-concrete (R-C) frames infilled with masonry walls, with- or without openings, are a common architectural element in low- and medium-height buildings. The infill walls stiffen the frame and reduce the first-mode period, leading to a reduction of drift response to strong ground motion. At the same time, the addition of masonry wall within the frame tends to increase the base-shear response and reduce the drift capacity of the structure. The increase of shear force and reduction of drift capacity leads to serious vulnerabilities unless proper proportioning is exercised. The specific flaws in unintentional frame-wall systems were identified in the aftermath of the Skopje earthquake of 1963. These were: (1) weaknesses introduced by openings in the wall, (2) captive columns, (3) out-of-plane collapse of walls, and (4) column failures under reversals of combinations of shear and tensile or compressive forces. These flaws have continued to cause tragic consequences in subsequent urban earthquakes [1].
The influence of openings in infill on the behaviour of reinforced-concrete frames infilled with masonry ("framed-wall") was experimentally investigated. Openings were of different types and positions and were executed with and without vertical confining elements around them. Ten specimens produced at a scale of 1:2.5, as practical true models, were tested under constant vertical and quasi-static cyclic lateral loading up to drifts when the infill failed. The frames were designed as medium ductility (DCM) bare frames. Masonry wall was produced with hollow-clay units and general-purpose mortar. The frame and masonry were connected only by cohesion (Fig. 1) [2]. Based on the experimental research, a macromodel was set up in the computer program DIANA FEA [3] and the analysis of a reinforced concrete frame with a masonry infill without openings was performed [4].

Figure 1. Specimens for laboratory investigation [2]

2 Macromodel

Due to the heterogeneity of the masonry infill, the construction of the computational model is more demanding. The requirement to know the properties of the material depends on the level of modelling and the type of calculation performed (e.g., linear or nonlinear). There are several possibilities or approaches to the modelling of masonry, such as those listed in [5-7], which are as follows: detailed micromodel; simplified micromodel or mesomodel and macromodel (Fig. 2).

The macromodelling approach selected and applied in this paper does not distinguish between individual wall elements and mortar joints and the infill wall is presented as a homogeneous anisotropic continuum. The chosen approach, in relation to the others, requires a significantly smaller number of material properties to feed the constitutive model, without consequences for accuracy in presenting the response of the structure. This simplification has made the modelling process more practical and it can be applied for analysis of not only individual walls but also complete buildings [8].

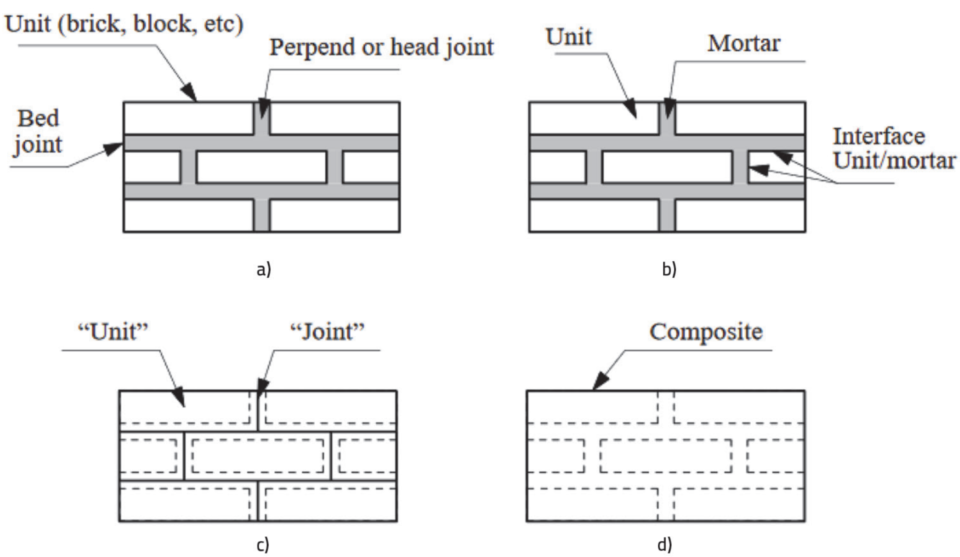

Figure 2. Modelling strategies for masonry: a) masonry wall, b) detailed micromodel, c) mesomodel (simplified micromodel), d) macromodel [5]

After earthquakes, field investigations and research results have shown that masonry infill placed within a structural RC frame ("framed-masonry") has both positive and negative effects on the seismic performance of the system. The new composite "framed-masonry" system has smaller drifts and deformations in structural members, together with shear resistance of higher storey and global energy dissipation. On the other hand, the infill wall presence can have an extremely negative effect on the surrounding frame in terms of shear failure of captive columns, depending on the wall strength, as given in [9] and [10].

Previous experiments have shown that even at small drifts (approximately 0.05 %) the infill wall behaves like a monolithic structure and the infill wall separates from the reinforced concrete frame. Increasing the floor displacement creates cracks along the formed compressive strut in the infill wall. In order to correctly present the separation of the infill wall from the reinforced concrete frame in the macromodel, it is necessary to apply a contact element at the joint of the frame and the wall, which has the possibility of gapping in tension. A detailed overview of the properties of constitutive models is given in [4], and due to the scope and lack of space it is not covered by this paper. The adopted macromodel is shown in Fig. 3. A mesh 100x100 mm was chosen using CQ16MEM membrane elements with quadratic interpolation (compatible with geometric nonlinearity).

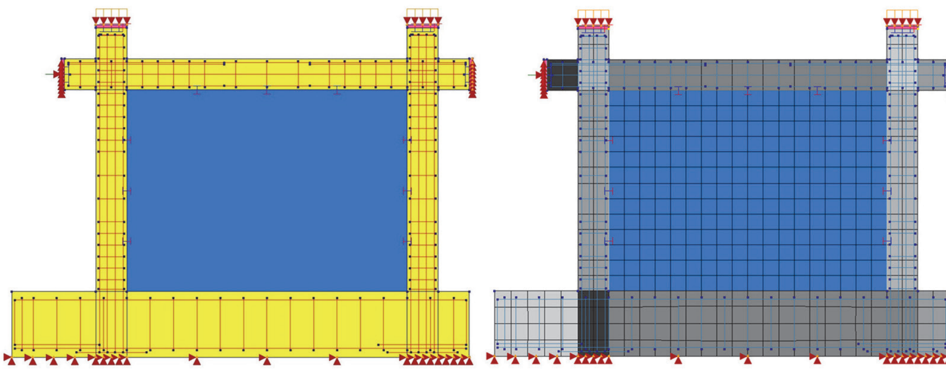

Figure 3. Macromodel and FE mesh (100x100mm) in DIANAFEA

3 Results

As in the experiment, the calculation was carried out entirely with force control. High sensitivity of the model to the properties of the contact elements placed between the frame and the infill wall was observed, which, in addition to physical ones such as initial shear strength, internal friction angle and tensile strength, also contain the so-called non-physical properties such as normal and tangential stiffness, the value of which needs to be assumed. For this reason, calibration was required. An additional problem arose when loading the structure model in the opposite direction (negative x-direction). It has been observed that during loading (when the beam is pulled) tensile stresses occur in the beam that exceed the value of tensile strength of the material, with large displacements. This problem was solved by introducing a rigid kinematic constraint, i.e., by equalizing the displacements in the longitudinal direction of the left and right ends of the beam.
Fig. 4 shows a comparison of the responses obtained from the experimental tests and the computational macromodel. The highest achieved load capacity and initial stiffness

in positive load cycles (positive x-direction) are in accordance with the results obtained by the test, while the corresponding values in negative cycles are 16 % lower. The difference in values arises from the ability to maintain a constant value of the longitudinal compressive force, and thus from the effect of friction of the movable supports with the tops of the columns (rollers). In the representation of the model given in Fig. 5, it is noticeable how the infill wall is crushed along the height of the column as well as in the corners of the frame (in red areas), which corresponds to the assumed behaviour of the structure and test results. Fig. 6 shows the separation of the infill from the surrounding concrete.

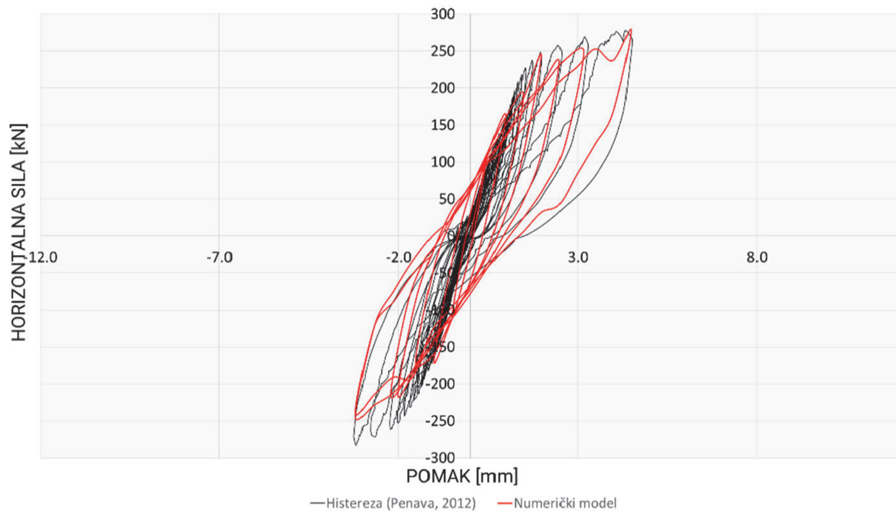

Figure 4. Hysteretic curves - comparison of experimental and numerical results

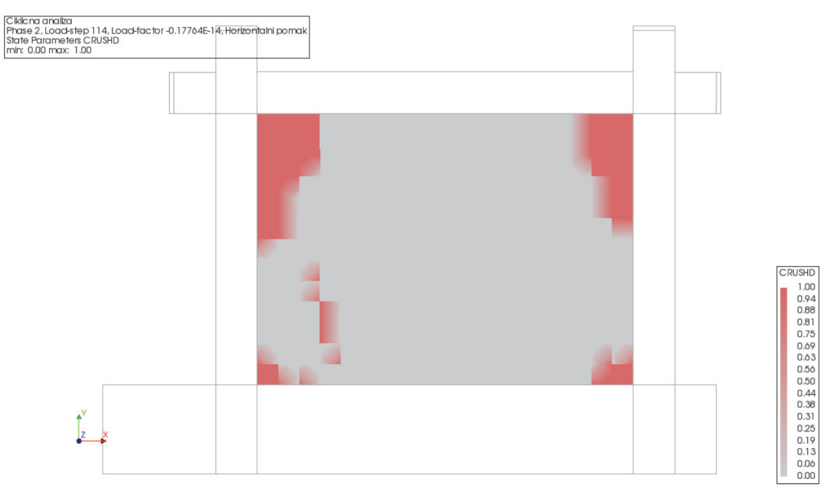

Figure 5. Crushing of masonry infill obtained by macromodel

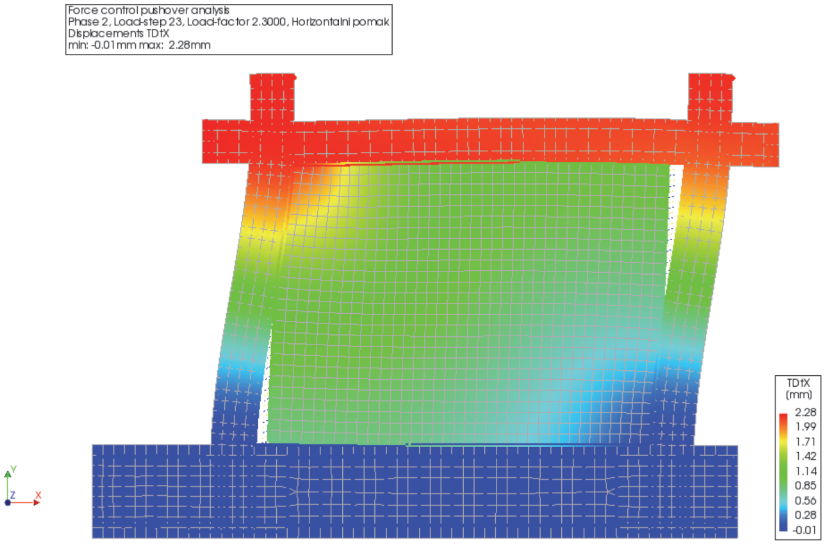

Figure 6. Separation of infill from RC frame in the opposite corners for imposed displacement of 2.30 mm

Development of damage in RC frame and masonry infill can be traced according to EMS-98 scale [11]. Key inter-story drift ratios (IDR) established by the experimental testing pertain to:

1. no damage
2. slight damage: IDR = 0.10 %
3. moderate damage: IDR = 0.25-0.30 %
4. heavy damage: IDR = 0.50-0.75 %
5. collapse: IDR = 1.0-1.25 %

Fig. 7 shows the degradation of stiffness for selected drifts. Specimens with full masonry infill (type III/2) and without masonry infill (type III/1) represent boundary cases. It can be noticed that the openings in the masonry infill reduce the stiffness of the system, but in relation to the frame without the masonry infill the stiffness is still significantly higher. As the damage increases, that is, the horizontal displacement, the rigidity of the system is expected to decrease. The largest differences in stiffness are at lower floor displacements. With a higher floor displacement, there is a small difference in stiffness for all specimens in relation to the reinforced concrete frame. With increasing damage to the masonry infill and larger floor displacement, there is a significant degradation of the system stiffness.

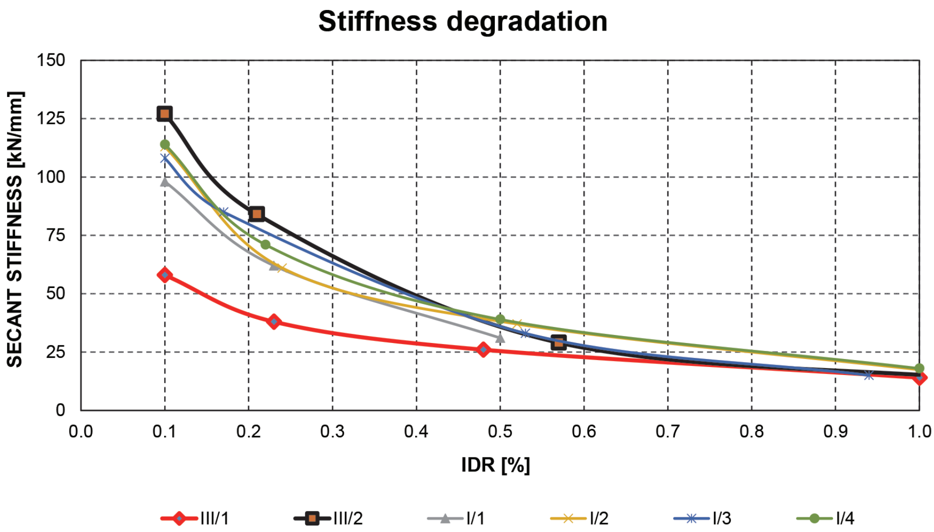

Figure 7. Degradation of secant stiffness for selected inter-story drifts

4 Conclusion

The described macromodel of the reinforced concrete frame with masonry infill, calibrated according to the test results, is able to present the most important response characteristics of these types of structures, which are: load-bearing capacity, stiffness and type of masonry failure. The calibration procedure showed a high sensitivity of the computational macromodel to the properties of the contact elements that represent the joints of the mortar at the contact of the infill wall and the reinforced concrete frame. Additionally, it was necessary to take into account the occurrence of friction on the rollers on the tops of the columns as described in [12], which is enabled by a spring with a bilinear constitutive model.

The selected macromodel is the simplest approach that can describe the behaviour of the infill wall using a computer program. It is capable of simulating test results with acceptable deviations. It does not require large data set of input parameters as with computational micromodels, which makes it more practical and the calculation faster.

References

[1] Sigmund, V., Penava, D. (2014): Influence of openings, with and without confinement, on cyclic response of infilled rc frames—an experimental study. Journal of earthquake engineering, 18 (1), 113-146, doi: https://doi.org/10.1080/13632469.2013.817362

[2] Penava, D. (2012): Influence of openings on seismic response of masonry infilled reinforced concrete frames. Josip Juraj Strossmayer University of Osijek, Osijek.

[3] TNO DIANA BV (2016): DIANA -User´s Manual. Delft, The Netherlands, 2016.

[4] Kadić, A. (2020): Numerical modeling of RC frame with masonry infill. Master Thesis, Faculty of Civil Engineering, University of Sarajevo.

[5] Lourenço, P. (1996): Computational strategies for masonry structures, PhD, Technical University Delft.

[6] Medić, S., Hrasnica, M. (2018): Modeling Strategies for Masonry Structures. Advanced Technologies, Systems, and Applications II. IAT 2017. Lecture Notes in Networks and Systems, vol 28. Springer, Cham, 12 pages, doi: https://doi.org/10.1007/978-3-319-71321-2_55

[7] Hrasnica, M., Medić, S. (2018): Finite element modeling of experimentally tested solid brick masonry walls, 16th European Conference on Earthquake Engineering, Thessaloniki 18-21 June, 2018, The European Association for Earthquake Engineering/Hellenic Society of Earthquake Engineering, 11 pages.

[8] Osmanović, N., Medić, S., Hrasnica, M. (2019): Seismic Assessment of Existing Masonry Building. Advanced Technologies, Systems, and Applications III. IAT 2018. Lecture Notes in Networks and Systems, vol 60. Springer, Cham, 10 pages, doi: https://doi.org/10.1007/978-3-030-02577-9_7

[9] ATC (1998): Evaluation of earthquake damaged concrete and masonry wall buildings: basic procedures manual (FEMA 306). ATC, Redwood City.

[10] Penava, D., Sigmund, V., Kožar, I. (2016) Validation of a simplified micromodel for analysis of infilled RC frames exposed to cyclic lateral loads. Bulletin of earthquake engineering. 14(10):2779-804, doi: https://doi.org/10.1007/s10518-016-9929-0

[11] Gunthal, G., Musson, R.M.W., Schwarz, J., Stucchi, M. (1993): The European macroseismic scale (MSK-92). Terra Nova, 5(3), 305-305, doi: https://doi.org/10.1111/j.1365-3121.1993.tb00261.x

[12] Penava, D., Sarhosis, V., Kožar, I., Guljaš, I. (2018): Contribution of RC columns and masonry wall to the shear resistance of masonry infilled RC frames containing different in size window and door openings. Engineering Structures, 172, 105-130, doi: https://doi.org/10.1016/j.engstruct.2018.06.007