Pushover analysis of R.C. framed structures with infill panels made of masonry having various properties

H A Mociran1* and N Cobîrzan1
1 Technical University of Cluj-Napoca, Faculty of Civil Engineering, Romania

* horatiu.mociran@mecon.utcluj.ro

Abstract. The seismic performances of R.C. frame structures were determined in terms of inter-storey drifts at two limit states, internal forces and moments (axial forces and bending moments), and the in-plane behaviour of infills. A nonlinear static analysis (pushover) was carried out in order to assess the seismic performance of buildings, to identify the expected plastic mechanisms and to plot the capacity curves. In pushover analysis, the vertical distribution of the monotonically increasing horizontal loads, was performed according to the first mode pattern. The nonlinear behaviour of structural members for pushover analysis was modelled by using the lumped plasticity, from where it derives that the potential plastic hinges were situated at the beams ends (which yield due to the bending moment), at the top and bottom of the columns at any storey (which yield based on the interaction of axial force and bending moment) and in the struts (which yield due to the axial force).

1. Introduction

Traditionally infill walls made of masonry, widely used on a large scale in the residential reinforced concrete framed structures [1], had a low performance at seismic actions [2, 3], in the last decades. In general, in the design practice, the infills are considered non-structural elements, thus they don’t influence the seismic response of buildings and are neglected in the structural analyses. As a function of the execution infills panels surrounding - frame connection, the predicted behaviour of the building structure can be altered from the one considered in the design phase [4], leading to different failure mechanism patterns in wall plane (sliding shear, diagonal cracking or corner crushing) and out-of-plane [5]. Significant damages to infill wall panels, caused by even the moderate earthquakes, yielded to large costs of repairing and strengthening [2, 3, 5], having as consequences the intensification of researches in this area.

In order to take into account, the favourable contribution of infills (energy dissipation capacity, increases of lateral stiffness and consequently diminishing the inter-storey drifts) to seismic response of reinforced concrete frames structures, many structural designers consider the infill-frame interactions with the surrounding frames on all edges of the infilled panels.

Regarding the modelling of infilled panels there are two main possibilities: micro-models and macro-models. In micro-models, the infilled panels are discretized in numerous finite elements (FE) [6], aiming a more accurate response of elements, at a high computational cost.

In contrast, in macro-modelling, the infills are considered as equivalent diagonal struts. Historically, first model being a diagonal strut, connected with hinges in the beam-columns joints, with the disadvantage of transferring the loads from the beam to the strut. Different simplified proposed models range from single to multiple diagonal pin-jointed struts, with various cross section width, disposed...
concentric or eccentric [7-12] with respect to the beam-column joint. Single equivalent strut-model assures a good balance between simplicity and accuracy in numerical analyses [4].

The seismic performance of structure is significantly influenced by the thickness and mechanical properties of the materials (units and mortars) used for infills. Considering the dynamics of occurrence of new masonry units with high thermal properties, with the aim to increase the energy performance of buildings, it is necessary to carefully investigate the seismic response of framed buildings with infilled panels made of such materials, placed in different seismic areas.

In that respect, the paper aims are to examine the influence of the mechanical properties of the materials used for masonry infills panels of reinforced concrete frame structure, upon the building seismic performance.

2. Materials and numerical simulations

A plane reinforced concrete frame, extracted from a typical 3D frame structure, located in Piatra Neamț, designed in accordance with regulation in force (code P100/1-2013 [13] and standard SR EN 1992-1 [14]) with medium ductility (DCM), was considered in this analysis. The frame has 5 floors and two bays of 5.0 m, the story height being 3.0 m (figure 1a).

| Case Study | Frame structure | Mechanical compressive strength [N/mm²] | Density [kg/m³] |
|------------|-----------------|----------------------------------------|-----------------|
| Benchmark  | Bare structure (benchmark) | | |
| 1st        | With infills    | 2.5 | 10 | 5 | 850 |
| 2nd        | With infills    | 2  | 10 | 10 | 850 |

The main characteristics of the design response spectrum used in the seismic analysis are: ground acceleration ($a_g = 0.25g$); corner period ($T_c = 0.7$ s); behaviour factor ($q = 4.725$).
In the benchmark reinforced concrete frame (1st case study), the effect of the infill panels was modelled as uniformly distributed loads on beams. The cross sections of all columns and beams are 40x40cm, respectively 30x40cm, determined from stiffness, ductility and fire considerations. The concrete class is C20/25 and steel grade is S500. The reinforcement of the frame members was computed in the benchmark structure, resulting for the longitudinal reinforcement of the columns 8 Φ16.

For the 1st and 2nd case studies, the dimensions of the cross-section members and their reinforcement was taken from the benchmark structure. The infill panels have been considered in full contact with the surrounding frames and have been modelled in accordance to seismic code P100-1/2013, through diagonal compression strut. The dimensions of diagonal strut were 25x60 cm. The values of the elastic moduli of the diagonal struts for the 1st and 2nd case studies have been 3382 N/mm² and 2667 N/mm², respectively.

The numerical analysis has been performed by using Finite Element Method (FEM) with SAP 2000 Educational [15].

3. Results and discussions
The seismic performances of reinforced concrete frame structures, are determined in terms of inter-storey drifts at two limit states (Serviceability Limit State (SLS) and Ultimate Limit State (ULS)), internal forces and moments (axial forces and bending moments), and the in-plane behaviour of infills. Also, a pushover analysis was carried out in order to identify the distribution of damages and to plot capacity curves.

3.1. Inter-storey drifts
The inter-storey drifts over the height of all analysed frames are displayed in figure 2.

![Figure 2. Inter-storey of all frame structures at: SLS (a) and ULS (b).](image)

It should be mentioned that the inter-storey drifts at SLS, in the 1st analysed case study, are closer to allowable drifts (dr,SLS = 0.005h) given by seismic design code, the stiffness conditions being fulfilled. By adding the infill panels, the inter-storey drifts at SLS (dr,SLS) and ULS (dr,ULS), were diminished by up to 89% - 93% in case study 1 and up to 87% - 91% in case study 2, compared with benchmark. As can be observed in figure 2, the reductions are approximately uniform at all stories.

3.2. Internal forces and moments
The axial forces (N) and bending moments (M), for central (cc) and marginal columns (mc) are shown in figures 3-4.

Considering the infill panels effect, the values of axial forces for marginal columns (Nmc) were increased at the first 4 floors up to 10% and diminished at the roof level up to 5%, compared with the bare frames. In contrast with the marginal columns, the axial forces of the central columns (Ncc), records decrease at all levels up to 24% (figure 3).
Figure 3. Axial forces for: central, $N_{cc}$ (a); marginal columns, $N_{mc}$ (b).

Regarding the values of bending moments for marginal ($M_{mc}$) and central columns ($M_{cc}$) were diminished up to 80%, respectively up to 97% in comparison with the benchmark (figure 4).

Figure 4. Bending moments for: central, $M_{cc}$ (a); marginal columns, $M_{mc}$ (b).

By analysing the previous results, it should be noted that by adding the infills, the behaviour of the structure is changed from a moment resisting frame, subjected mainly to bending moment, into a truss type structure. This yields to important reductions of the values of bending moments in all columns and negligible changes of axial forces.

3.3. In-plane performance of infills

The in-plane performance of infills, was analysed by investigating the three possible failure patterns: sliding shear, diagonal cracking, and corners crushing (figure 5b).

The axial forces in diagonal struts ($N_d$) versus the design values of resistance of infill panels ($FR_{d1}$, $FR_{d2}$, $FR_{d31}$, $FR_{d32}$), for frames analysed in case studies 1.2, are presented in figure 5.
In both cases, at the lower level, the axial forces in diagonal strut exceed the design values of resistance of infills. In order to avoid the corners crushing failure of infills three other solutions have been proposed: masonry made of clay units from group 2S, with superior compressive strength, $f_{bh} = 4\text{N/mm}^2$ (case study 1.1); masonry made of units from group 2S, with superior compressive strength, $f_{bh} = 3.5\text{N/mm}^2$ (case study 2.1) respectively, units from group 2 instead of 2S with $f_{bh} = 4\text{N/mm}^2$ (case study 2.2). The elastic moduli of the diagonal struts of the case studies 1.1, 2.1 and 2.2 have been determined as follows: 3647 N/mm$^2$, 2917 N/mm$^2$ and 2963 N/mm$^2$, respectively.

By considering infills panels made of materials with improved mechanical properties, the axial forces induced in struts by seismic actions increase, in case of study 1.1 up to 2.88% with respect to case study 1, and in case studies 2.1 and 2.2 up to 3.56% respectively 4.20% in comparison with the case study 2 (figure 5a). It is worth to mention that the new obtained values are lower than the design values of resistance of infills (figure 5b).

3.4. Pushover analysis

Also, a nonlinear static analysis (pushover) was carried out in order to assess the seismic performance of the building, to identify the expected plastic mechanism and to plot the capacity curves.

In pushover analysis, the vertical distribution of the monotonically increasing horizontal loads, was according to the first mode pattern. The nonlinear behaviour of structural members for pushover analysis was modelled by using the lumped plasticity. The potential plastic hinges are situated at the beams ends (which yield due to the bending moment), at the top and bottom of the columns at any storey (which yield based on the interaction of axial force and bending moment) and the strut (which yield due to axial force). Also, the geometrical nonlinearity (second order effect) was considered.

In figure 6 is displayed the plastic hinge configuration at the collapse mechanism of the structures.

The seismic performance of the building was investigated at SLS and ULS, considering the allowable interstorey-drifts corresponding to the both limit states, prescribed by the seismic code, the pushover curves and the sequence of plastic hinge appearance.

Regarding the SLS performance, it was noticed in all cases that damages to infill panels extended from the base to upper floors. As expected, the worst behaviour was recorded in case study 2 where the design value of resistance of infill panel was the lowest, while the best performance was attained in the proposed solutions (case studies 1.1, 2.1 respectively 2.2), where the infills were destroyed entirely in the first three floors and partially at the fourth level.

Concerning the ULS, the behaviour of frame members was similar for all cases, with plastic hinges at beams ends in the first three levels and at the base of the columns. The worst seismic performance of the infill was achieved in case study 2, where all the panels were damaged.
In contrast, the best seismic response was noted in case study 2.2, with the maximum design value of resistance of infill panel, where only the panels for the first fourth floors were damaged.

Other pushover analyses carried out by several authors [16], had revealed that infilled damages are first meet at the lower level of the buildings.

![Figures](a) (b) (c) (d) (e) (f)

**Figure 6.** Plastic hinge configuration at collapse mechanism: benchmark (a); case study 1 (b); case study 1.1 (c); case study 2 (d); case study 2.1 (e); case study 2.2 (f).

### 4. Conclusions

In this paper the influence of the material properties used for masonry infill panels of R.C. frames upon the overall seismic performance of the buildings has been investigated by means of modal seismic response spectrum and pushover analyses.

The following conclusion can be drawn:

- the inter-storey drift at SLS and ULS were diminished approximatively uniform at all stories up to 93% in both case studies compared with benchmarks;
- the values of bending moments in all columns were reduced up to 97% in case studies 1 and 2 while the values of axial forces were changed insignificantly in comparison with the benchmark. Thus, the behaviour of the structure has been changed from a moment resistance frame into a truss type structure;
- the mechanical properties of masonry units used for infilled panels influence significantly the in-plane performance of infills;
- in all cases the seismic performance of infills was related to design values of their resistance.

The results obtained in these numerical analyses highlight that seismic performance of the buildings with R.C frame structure is depending on mechanical properties of masonry used for infill panels.
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