# PARAMETRIC EVALUATION OF THE RESPONSE OF INFILLED RC FRAMES BUILT IN QUEBEC BEFORE 1960 UNDER SEISMIC LOAD

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## ABSTRACT

Frames infilled with brick masonry represent an important part of the historical buildings stock found in Montreal and other cities in Quebec, which is representative of the construction in eastern North America. Among this general structural typology, reinforced concrete frames erected before 1960's, are known to present some deficiencies affecting their lateral capacity. Moreover, the interaction between concrete and masonry is still unclear. The first objective is to proceed to a structural characterization of this typology. The second objective is to increase the precision of the seismic vulnerability evaluation for this kind of structure through a better understanding of the response under lateral loads and on how geometrical and modelling parameters affect the response. This paper presents a parametric study on the influence of different parameters on the linear response and nonlinear response of infilled RC frames under seismic load. The results will be used to develop an improved simplified model for the infill. A set of parameters (height to width ratio, number of storeys and bays, openings, modelling techniques, etc.) is evaluated under modal, static linear/nonlinear and dynamic nonlinear analyses. Linear and modal analyses have been completed. The preliminary results show that geometric parameters such as infill thickness, column dimensions and story height are not very influential. Modelling of upper storeys and types of openings are the two parameters that will be considered in the upcoming static and dynamic nonlinear analyses.

**KEYWORDS**: seismic, brick masonry, infill, RC frame, existing structure, seismic vulnerability

## INTRODUCTION

Existing buildings constructed prior to the implementation of seismic codes are considered to be highly vulnerable to earthquakes. Among those buildings, reinforced concrete frames with unreinforced brick masonry infills are common in the Province of Quebec, as well as in North America. In fact, this structural typology is widespread all around the world with some construction particularities depending on the region. These buildings are used for offices, residences, hospitals and schools, some of which should be able to play an important role in post-earthquake situation (care establishments and shelters).

The seismic risk related to a structure is a combination of the seismic hazard, its social and economic value and its structural vulnerability. A precise seismic vulnerability evaluation can be used to predict potential structural damages under different earthquake scenarios. It requires the use of models that represent adequately the structural characteristics of the buildings and its response under seismic load. Structural characterization is therefore one of the first steps required to develop such models.

We know from past earthquakes that reinforced buildings (RC) with infills constructed before 1960's are vulnerable to lateral loads. Among the possible structural damages these structures could experience are the out-of-plane failure of the infills, propagation of cracking from masonry to concrete elements, collapse of a soft story, rupture of "captive" columns (created with partial infills), detachment of masonry veneer, shear cracking of the column due to masonry compression strut, and so on.

However, there is still no consensus about the interaction between the concrete frame and the infills. For example, it is still frequent to evaluate the lateral resistance without considering the contribution of the masonry. Most engineers agree that this typology is an unfavourable combination of two different construction methods: ductile and flexible frames with rigid and fragile masonry. Others [1-3] observed that the material combination increases the global resistance. As illustrated in Figure 1, masonry infills contribute to the global resistance of the structure, even after its failure. This contradicts the common thinking considering that residual resistance should be equal to the bare frame resistance after failure of the masonry. Unreinforced masonry is a brittle material often simplified as linear material. A major challenge remains: how to model the infill and contact zones with frame in a simple and efficient way? Should a residual resistance be considered?

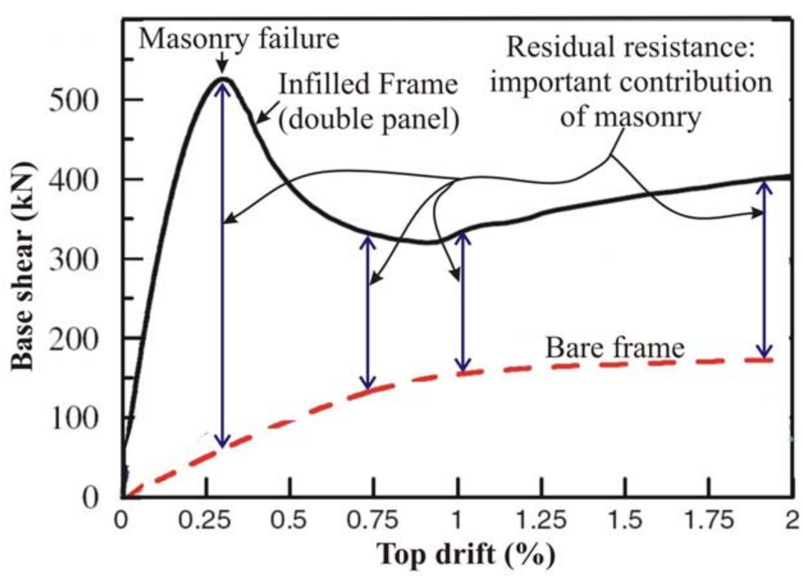



**Figure 1: Contribution of masonry infills [adapted from 3].**

The global objective of this research project is to characterize the seismic behaviour of the brick infilled RC buildings built in Quebec before 1960's. This paper presents the results of the first steps of this project: (i) the structural characterization of the studied typology and, (ii) a parametric evaluation of static linear and modal responses. Static and dynamic nonlinear analyses will next be performed to allow the development of a realistic seismic behaviour model adapted to the studied infilled RC structures.

## SEISMIC CONTEXT OF THE PROVINCE

Eastern Canada is a stable continental region and consequently, has a relatively low rate of earthquake activity. Nevertheless, large and damaging earthquakes have occurred in the past and will inevitably occur in the future. The Charlevoix Seismic Zone, located 100 km downstream from Quebec City, is the most seismically active region. This zone has been subjected to five earthquakes of at least Richter magnitude 6 between 1663 and 1925 [4]. The Western Quebec Seismic Zone, which encloses the Ottawa Valley from Montreal to Temiscamingue, was the site of three significant earthquakes with local magnitudes near 6 in 1732, 1935 and 1944. In November 1988, an earthquake of surface wave magnitude 6 occurred in the Saguenay region, causing tens of millions of dollars in damage. Damages were observed in brick infilled RC buildings such as diagonal cracking and partial out-of-plane failure of the infills [5].

Although these events are rare, compared to the seismic activity in Western Canada and California, their economic and social effects cannot be neglected. Reduction of potential damage caused by earthquakes requires relevant remedial measures that can be adequately defined by representative analytical models of the most vulnerable typologies.

## METHODOLOGY

The first step of this project is the structural characterization of infilled reinforced concrete frames of Quebec structures built before 1960's. The results of this characterization are the geometrical and material properties used for modelling the infills and the RC frames.

Following the characterization of brick infilled reinforced concrete frames, a set of parameters potentially influential were defined. The studied parameters are: height to width ratio, number of storeys and bays, openings, column dimensions, infill thickness and modelling techniques (struts / shells). Linear analyses are conducted to identify geometric and modelling parameters having a critical influence on the response of the models. We expect that the same parameters will be critical in nonlinear analyses; so this step is useful to identify the most influential parameters that will be considered in nonlinear analyses.

Two responses were analysed for static linear analyses: displacement at the top of the building (D) and interstorey drift. Displacement is used to calculate the global rigidity of the structure which provides information about linear portion of load–displacement curve. It also gives a magnitude of displacement expected in nonlinear domain. Interstorey drift response is useful to assess the influence of soft story.

One of the parameters evaluated is the modelling technique of the infills. Two modelling techniques are available to consider the infills: compressive struts and finite element modelling with shell elements. Modelling by compressive struts, initially proposed in the sixties, neglects some important characteristics of the structural behaviour, such as the contribution from gravity load, the forces developed at the concrete – masonry interface and the presence and dimensions of openings. Finite element analyses (FEA) are accurate in linear domain but remain unable to properly represent large displacements caused by element separation and progressive collapse of structures which are characteristics of seismic behaviour. This can be achieved by the use of applied element method [6].

## CHARACTERIZATION OF INFILLED REINFORCED CONCRETE FRAMES

Several examples of existing brick infilled RC frames constructed before 1960 can be observed in Montreal and in other urbanized areas in the province. Most of the time, the concrete elements are exposed on the sides and/or the rear of the buildings, because of the method of construction where the insulation is on the inside of the structure (see examples in Figure 2.a, b and c).

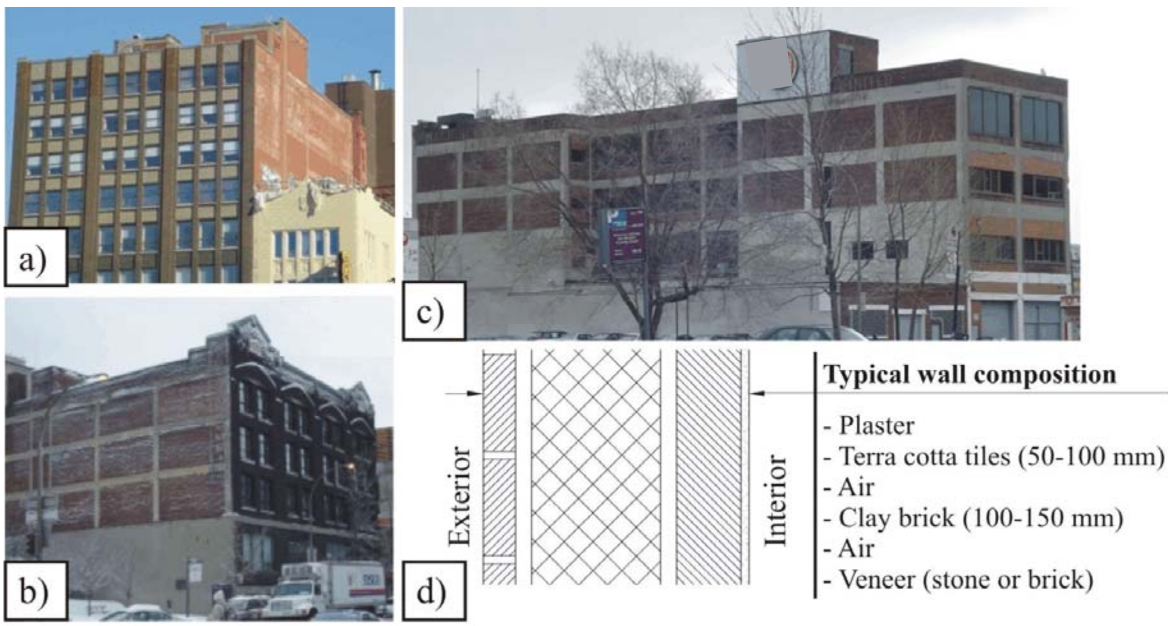



**Figure 2: a, b, c) Examples of infilled RC frames in Montreal; d) Typical wall composition.**

It is essential to underline that there is a huge variability in the construction methods, quality of the global structures and properties / quality / types of building material. This variability depends on regions, years of construction, workers skills, etc. An extensive research was done to characterize as precisely as possible the brick infilled RC frames erected in province of Quebec between 1915 and 1960. Multiple sources were consulted: literature (papers and official publications), experimental reports of tests on materials withdrawn from existing structures in the province and discussions with experimented engineers working mainly in structural rehabilitation domain. Some of these references are identified in Table 1.

One important result is the characterization of a typical perimeter infill wall, as illustrated in Figure 2.d. These walls have a total width of structural masonry varying between 150 and 250 mm. Veneer is excluded from this width because it is located outside the frame elements. Interior infill walls (partitions) could be constructed with only one type of structural masonry (clay brick or terra cotta tiles 100-150 mm) and plaster finish. Often, there is a cavity for mechanical purposes. All the geometrical and material parameters needed to generate analytical models are listed in Table 1.

**Table 1: Geometrical and material properties for the modelling of brick infilled RC frames typical of province of Quebec (1915-60)**

| **Geometrical properties** | **Value** | **Units** |
|---|---|---|
| Number of storey | 1 or 3 | -- |
| Height of storey | 3, 4 or 5 | m |
| Width of bays | 4, 6 or 8 | m |
| **Concrete elements properties** | **Value** | **Units** |
| Beams, reinforcing steel 1% (6 bars $\phi$ = 20 mm) [7] | 300 x 600 | mm |
| Square Columns, reinforcing steel 0.5–1.5% (8 bars $\phi$ = 25 mm) | 450 or 600 | mm |
| Concrete, compression limit [8-11] | 21 | MPa |
| Concrete, elasticity modulus | 23.2 | GPa |
| Reinforcing steel, plastic and ultimate limits [9-12] | 300 and 475 | MPa |
| Reinforcing steel, elasticity modulus [7] | 225 | GPa |
| **Masonry elements properties** | **Value** | **Units** |
| Structural masonry width : clay brick 100-150 + terracotta 50-100 [13] | 0, 150 or 250 | mm |
| Masonry shear [8, 14], compression [15, 16] and tension [16] limits | 0.2 ; 8.3 ; 0.4 | MPa |
| Masonry, elasticity modulus [17] | 4.5 | GPa |

## LINEAR STATIC ANALYSES

Linear static analyses are performed to determine critical individual parameters as well as interactions between those parameters. Because of the large number of variables, analyses were separated in two phases. While phase 1 considers most geometrical and modelling parameters, as described in Table 2, phase 2 focuses on types of openings using FEA with shell elements (Table 3). The models were generated using the general structural analysis software SAP2000 [18]. The models have fixed base, beam-column joints perfectly rigid, shells are shell-thin elements and struts dimensions were calculated according to FEMA356 [10].

### a) PHASE 1

Phase 1 studies 7 parameters as listed in Table 2. Among the 360 possible combinations, 58 models were selected in a reduced experimental plan to evaluate the influence of the parameters and their two-by-two interaction. Before running the analyses, the seismic weight (W), the equivalent static load (V) and its distribution along the height of the structure were calculated in accordance with the NBCC 2005 [19].

**Table 2: Parameters tested in phase 1 – linear static analyses**

| **Parameters** | **Units** | **Possible values (weight, %)** | | |
|---|---|---|---|---|
| Infill modelling | -- | Strut (40%) | Shell (42%) | n.a. (18%) |
| Infill width | mm | 0 (19%) | 150 (40%) | 250 (41%) |
| Bay width | m | 4 (34%) | 6 (32%) | 8 (34%) |
| Storey height | m | 3 (33%) | 4 (33%) | 5 (34%) |
| Soft story (presence) | -- | Yes (21%) | No (21%) | n.a. (58%) |
| Number of storey | -- | 1 (50%) | | 3 (50%) |
| Column dimensions | mm | 450 (50%) | | 600 (50%) |

Global rigidity values were computed from the top displacements. Using Statgraphics software [20], a linear regression analysis was conducted with descending single step method to define the relation between the rigidity response and significantly predictive variables. These significantly predictive parameters are: bay width, number of storey and infill modelling. As expected, rigidity is inversely proportional to the number of storey; directly proportional to bay width and increases if infills are modelled with shells instead of struts. Two of these relations are illustrated in Figure 3 below (bay width and infill modelling).

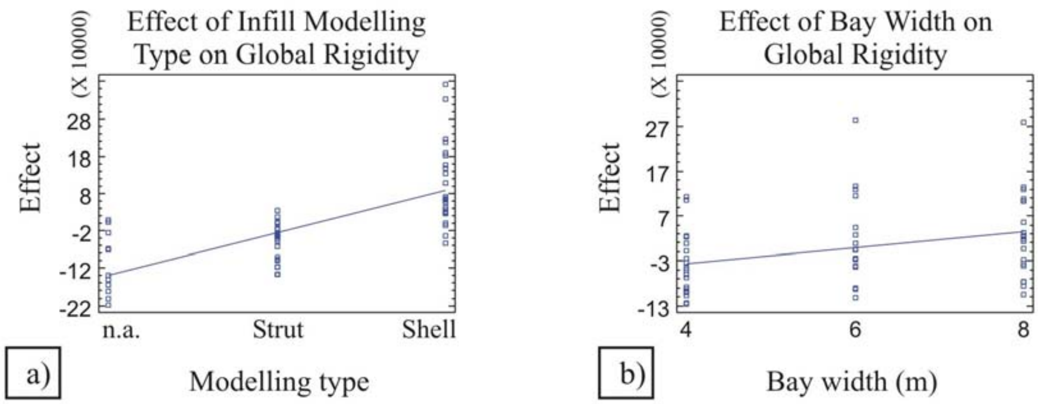



**Figure 3: Influence on rigidity response of a) masonry infill modelling type; b) bay width.**

As illustrated in Figure 3, the type of modelling influences considerably the global rigidity. Among the 58 models, the results in rigidity of four pairs of models using either struts or shell modelling were analysed. The global rigidity for the shell models is in average four times the one obtained with the strut models (this ratio varies from 3.1 to 5).

Among the evaluated parameters, the presence of a soft storey is known to increase significantly the displacement of infilled RC frames. This increased flexibility is not observed at the top but at the level of the soft storey. As expected, this is confirmed by the results of the interstorey drifts. Figure 4 shows interstorey drifts for strut models having three storeys, with and without soft storey at the ground floor. Graphs for shell models (not shown) have the same appearance, with a maximum interstorey drift of 0.4% instead of 0.8%.

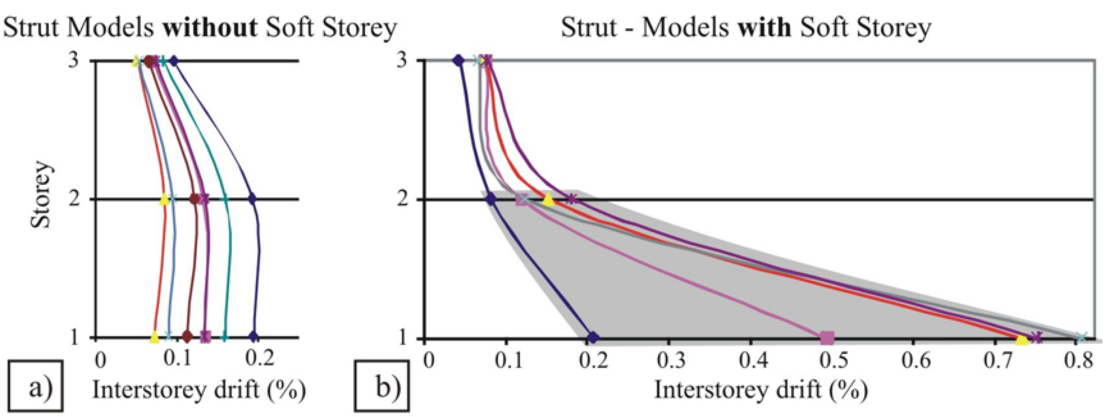



**Figure 4: Interstorey drift for strut models (a) without; (b) with soft storey.**

b) PHASE 2

In phase 2 of linear static analyses, only shell modelling was used to capture the influence of different types of openings (dimension and position) with and without soft storey. All the models have three storeys. Mean values are fixed for geometric parameters already evaluated in phase 1: bay width = 6 m, storey height = 4 m, infill width = 200 mm and column dimensions = 600 mm. Table 3 shows the 5 types of openings considered along with the 3 other variables defining the models. The full experimental plan includes 40 models using shell elements.

**Table 3: Parameters tested in phase 2 – linear static analyses**

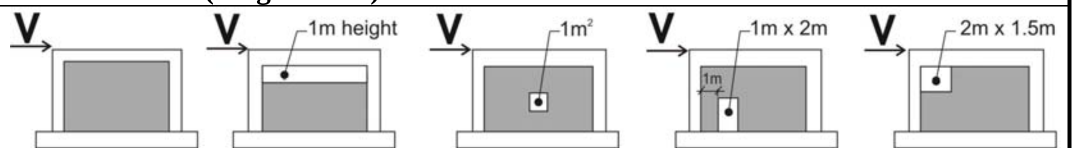
| Parameters | Possible values (weight en %) | |
|---|---|---|
| 5 types of Openings (20% each) |   | |
| Modelling of upper storeys | Upper storeys modelled (50%) | Concentrated loads replace upper storeys (50%) |
| Bay number | 1 (50%) | 3 (50%) |
| Soft story (presence) | Yes (50%) | No (50%) |

Figure 5 illustrates the effect of top and central openings on the deformed shape and the stress distribution for 1-bay 3-storeys models without soft storey. The compressive paths are clearly shown on stress diagrams of each model as well as stress concentration at the opening's corners.

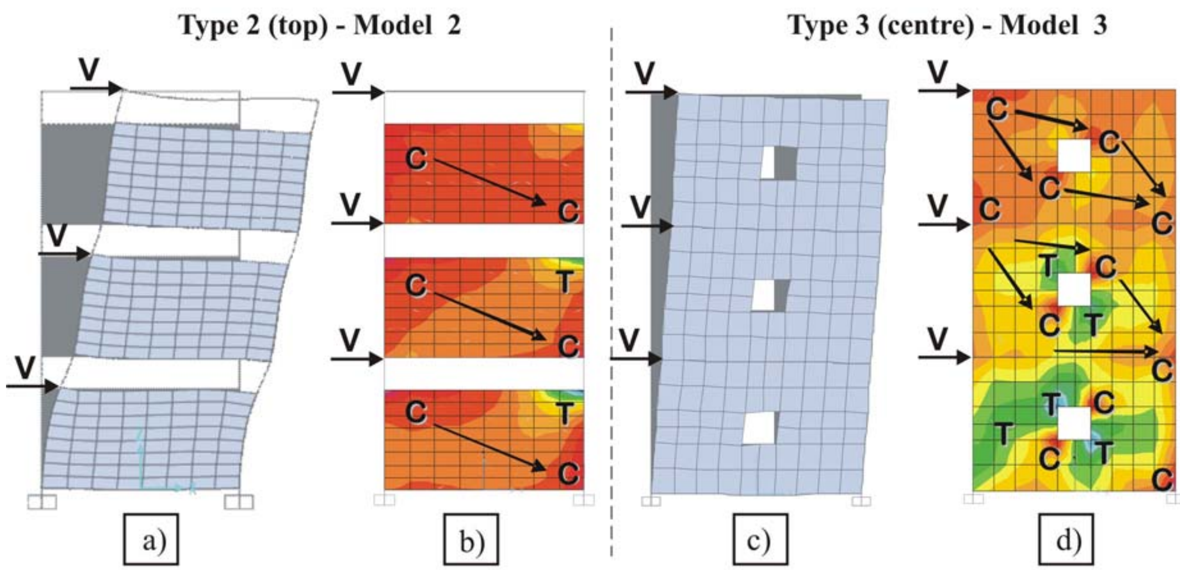



**Figure 5: Models 2 and 3: Deformed shape (a, c) and Stress diagrams (b, d).**

Model 2, with openings creating "captive" columns, exhibits large displacements due to its reduced rigidity (Figure 5.a) and the increased shear effect at the level of these columns. The interstorey drift at the first level of this model is 2.3 times larger than the one of model 1 without opening. Model 3 with center opening (Figure 5.c), exhibits nearly linear displacement illustrating that its rigidity is not affected by this type of openings.

A linear regression analysis on global rigidity response indicates the significantly predictive variables: number of bays, presence of soft story and modelling of upper storeys. The increase of rigidity of 3-bays models is not proportional to the number of bays, varying between 3.2 to 3.4 times the rigidity of the 1-bay models. Modelling of upper storeys tends to increase rigidity while, as expected, the presence of a soft story decreases it. The types of openings do not influence the rigidity response, but affect the deformation shape (see Figure 5).

According to the results of the static linear analyses, influential parameters that should be considered in the nonlinear analyses are: bay width (4, 6 or 8 m), number of storey (1 or 3), infill modelling (strut or shell), presence of soft story, modelling of upper storeys / punctual loads, number of bays (1 or 3) and types of openings (dimension, location).

## MODAL ANALYSES

Modal analyses were performed on 60 models, according to a full experimental plan, in order to evaluate the effect of most influential parameters identified by linear static analyses excluding soft storey and bay width. Considered parameters are: 5 types of openings, number of storeys (1 or 3), number of bays (1 or 3), upper storeys (modelled or replaced by concentrated loads) and infills modelling (struts or shells).

Results show that the infill modelling type is a predictive variable for the natural period. This means that strut and shell models do not give identical periods, shells models being more rigid, as shown previously, periods tend to be shorter. Modelling of upper storeys or its replacement by concentrated loads is predictive for the fundamental period, while opening types tend to modify higher modes. Modal shapes indicate that the first mode is always a shear mode, while second and third modes are bending.

## EFFECT OF CONTACT LENGTH

The linear static analyses models with shell elements have full contact between masonry and concrete. This full contact did not allow separation between the different materials, which is unrealistic in tension zones. Some tests were done to increase the precision of the models. The ratio of compression length was determined by trial and error and confirmed by literature [21, 22]. This ratio is 0.6 for beams and 0.5 for columns. In tension zones nodes of masonry shell elements and concrete beams/columns should be unconnected.

## NONLINEAR BEHAVIOUR: FUTURE WORK

The objective of upcoming nonlinear analyses is to verify the contribution of masonry to resistance as illustrated in Figure 1 and described in previous work [2, 3, 23, 24]. Nonlinear static analyses will be first performed using struts or finite element to obtain the capacity curves of models having different openings, number of bays and number of storeys. Models will include plastic hinges in the concrete columns and the masonry struts and nonlinear behaviour of the materials (concrete and masonry) [2, 25]. Then, dynamic nonlinear analyses using applied element method will allow representing large displacements caused by element separation in tension zones and progressive collapse of structures.

## CONCLUSION

This paper presents a parametric study to evaluate the influence of a set of variables on the linear static response and modal response of existing brick infilled RC frames. The objective is to gain a better understanding of their response under lateral loads. The parameters identified as influential are: bay width, number of storeys, infill modelling, soft story, modelling of upper storeys / punctual loads, number of bays and types of openings. Besides the obvious influence of soft storey, the most influential parameters are the modelling technique for masonry, the modelling of upper storeys and the types of openings.

In the context of seismic evaluation of an existing structure, a practical model should be develop to represent adequately the structural characteristics and behaviour of brick infilled RC frames including residual resistance of the masonry. A strut model with plastic hinges will be proposed. Calibration of geometric and material properties will be done by static and dynamic nonlinear analyses using applied element method and considering modelling of upper storeys and opening types.

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