MECHANICAL INTERPRETATION OF INFILLS-TO-FRAME INTERACTION: CONTRIBUTIONS TO THE GLOBAL BASE SHEAR FOR STRUT-BASED FRAME MODELS

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ABSTRACT

The presence of infills has substantial effects on the behaviour of frame structural systems, both in the linear and non-linear behaviour. Different effects might arise at global (increase in strength and stiffness, modification of the plastic mechanism) and local level (e.g. triggering of shear failures in the columns). The global effects can be captured by adopting numerical macro-models (e.g. representing the infill panels as equivalent struts), while local effects can be typically better captured by using FEM micro-modelling. Focusing on single- or multiple-strut macro-modelling strategies, in this paper a mechanically-based procedure to decouple the frame and infills contributions to the overturning moment (and hence base shear) capacity for any value of the global displacement is proposed. The method is applicable regardless of the distribution of the infills and of the non-linear Axial load-Axial strain relationship of the equivalent struts. For these reasons, such procedure can be applied to post-process the results of non-linear pushover or time-history analyses of different types of infilled frames (material-wise) as well as be adopted as a simplified analytical approach, such as SLAMA (Simple Lateral Mechanism Analysis), to derive the capacity curve of an infilled frame whilst capturing the proper internal actions. An application of the method on an experimentally-tested one-storey one-bay masonry infilled frame is used to calibrate the adopted numerical model. Furthermore, the method is applied to the pushover analysis of a two-storey one-bay masonry-infilled RC frame, with uniform or “pilotis” infill distributions, modelled by means of a single-strut approach. The results confirm the suitability of the proposed method in decoupling the frame and infills contributions to the total overturning moment.

Keywords: Infilled structures; Non-linear analysis; Infills-to-frame interaction; Strut-based model; Overturning moment

1. INTRODUCTION

The presence of infill walls in frame structural systems plays a major role in the definition of their mechanical response under lateral forces, both for the linear and non-linear behaviour (Magenes and Pampanin, 2004). Damage observations from past earthquakes confirmed this phenomenon (e.g. Del Vecchio et al., 2017). Typically, the infill-related effects on frame structures are grouped in two categories: local and global effects. The first category refers to a significant modification, with respect to the bare frame configuration, of the distribution of the internal actions. In turn, this might trigger a number of failure mechanisms in the structural members, e.g. shear failure in joint panels or columns. To capture local effects, micro-modelling techniques are more typically adopted, in which masonry bricks and mortar are explicitly modelled by means of Finite or Discrete Element Modelling approaches. Such techniques guarantee a high level of detail, provided that a large number of parameters is calibrated, but require high computational demand and considerable effort in the interpretation of the

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results.
For such reasons, macro-modelling techniques are widely adopted (summarised for example in Crisafulli et al., 1997 and synthetically shown in Figure 1). In this trade-off, computational cost is considerably reduced but the ability to capture local effects due to presence of infills is partly lost. On the other hand, global effects can be reasonably well captured, including the increase in strength and stiffness with respect to the bare frame configuration, and possibly a change in the global plastic mechanism (e.g. triggering of a soft-storey). Due to its simplicity and overall efficiency, the most adopted macro-modelling techniques is the single equivalent strut approach, in which each infill wall is modelled with two diagonal struts that resist compression only. A slightly more refined technique is the multi-strut approach, in which two or more struts are used for each diagonal of the infill panel.

When a single- or a multi-strut approach is adopted, the effects of the infills on the single RC members is typically estimated by post processing the records of the internal actions. Regarding the global response of the frame, the influence of the infills might be for simplicity estimated by running two numerical non-linear analyses, on the bare frame and on the infilled frame configurations, and subtracting the first curve from the second. Firstly, this introduces a bias in the estimation, since the two analyses are not correlated and therefore the infill-to-frame interaction is not properly taken into account. Secondly, two non-linear analyses – either pushover or time-history - are needed. To overcome this issue, in this paper a mechanically-based approach is proposed to decouple the frame and the infills contributions to the overturning moment (and hence base shear) capacity for any value of the global displacement. The decoupling procedure is applicable regardless of the distribution of the infills, i.e. uniformly distributed, pilotis, etc., and of the non-linear Axial load-Axial strain curve of the equivalent struts. For these reasons, such a procedure can be applied to post-process the results of non-linear pushover or time-history analyses of different types of infilled frames (in terms of geometry and materials). Moreover, and to some extent of more interest, the proposed procedure can be adopted within analytical methods for non-linear static analyses of structures, such as the Simple Lateral Mechanism Analysis, SLaMA (NZSEE 2017). This “by-hand” pushover method is applicable to RC frame structures (Del Vecchio et al., 2017a,b, Gentile et al., 2017a,b) and is currently being improved and extended to masonry-infilled RC frames (Gentile, 2017), based on the interpretation of the infill-to-frame interaction proposed in this paper.

The mechanical decoupling procedure is firstly outlined. Therefore, the suitability of the decoupling procedure is demonstrated through its application to the pushover analysis of a two-story one-bay frame with three different infill distributions: bare, uniformly infilled and pilotis (where the infills are missing at ground level). The adopted numerical model is firstly calibrated against the experimental test of a one-bay one-level infilled frame (Calvi and Bologini, 2001).
2. INFILL-TO-FRAME INTERACTION: PROPOSED MECHANICAL INTERPRETATION

The decoupling procedure herein proposed, applicable to either a single- or a multi-strut macro-modelling, is herein for simplicity discussed considering a single-strut numerical model, with the masonry struts connected to the beam and columns end sections by means of rigid arms able to carry compression only. Such modelling approach (introduced in Magenes and Pampanin, 2004 and shown in Figure 5) is deemed to allow for a more realistic shear transfer to columns and beam-column joints (Figure 10). This modelling strategy is discussed in detail in Section 3.1 and its implications on the distribution of the internal actions is discussed in Section 3.3. However, it is worth mentioning that the decoupling procedure is entirely valid even for the more common modelling strategy in which the masonry equivalent struts are directly connected to the centroid of the beam-column joints.

Within a single step of a non-linear analysis, the superposition principle can be considered valid and any decomposition of the acting forces, and related internal actions, would therefore be allowed. Figure 2 shows a particular application of this process for a pushover analysis (although the application to a time-history is conceptually identical). The infills are firstly substituted with the internal forces that they apply to the frame (namely, their axial load \( P_{ij} \), where \( i \) is the number of the level and \( j \) is the number of the considered bay, Figure 2.b). The strut forces are then decomposed into their horizontal and vertical components, according to the inclination \( \theta_{ij} \) of the struts. Finally, the whole structural scheme can be represented as the sum of two sub-schemes: one in which the external forces \( F_1 \) are applied together with the horizontal components of the strut forces (Figure 2.c) and another in which only the vertical components of the infill forces are applied (Figure 2.d).

![Figure 2](image)

Figure 2. Contributions to the base shear from the frame and the infills: superposition principle in a general step of a non-linear analysis.

The former can be also interpreted as a bare frame structure loaded with a force pattern, \( F_1 \) (Eq. 1), modified from the original pattern, \( F_2 \), i.e. external load pattern in a pushover or storey shear forces in a time-history analysis. The modified pattern \( F_1 \) embeds the horizontal components of the strut forces, and hence it is deemed to change at each step of the non-linear analysis depending on the axial loads in the equivalent struts.
\[ F_i = F_i + \sum_{j} P_{i+1,j} \cos \alpha_{i+1,j} - P_{ij} \cos \alpha_{ij} \]

The latter scheme (Figure 2.d), where only the vertical components of the strut forces are applied, allows to calculate the influence of the infills in resisting the overturning moment. In particular, the vertical components of the strut forces become shear in the beams and, in turn, axial load in the columns \((\Delta N_{\text{inf},j})\). This creates the tension-compression couple that contributes to resist the overturning moment due to the applied external forces \(F_i\), calculated with Eq. 1. In principle, the internal actions (in particular shear and bending moment) associated to the vertical components of the strut forces can thus theoretically influence the above-mentioned overturning-resisting mechanism. However, it was noted that these internal actions are typically negligible, and therefore this effect is not considered. This applies a fortiori if the equivalent struts are directly connected to the beam-column joints centroids.

\[ \text{OTM}_{\text{inf}} = \sum L_{\text{bay},j} \Delta N_{\text{inf},j} = \sum L_{\text{bay},j} P_{ij} \sin \alpha_{ij} \]

This overturning-resisting mechanism works in addition to the typical mechanism of a bare frame, i.e. sum of the base column moments plus the tension-compression moment couple coming from the sum of the beam shears (this is shown in Figure 3 for a general configuration of the frame and a general distribution of the infills). Due to the above-mentioned modified force pattern, the internal actions distribution on the frame members is affected and, as a result, the overturning-resisting mechanism related to the frame members is modified with respect to the typical behaviour of a bare frame, especially when the contribution of the infills is maximum.

![Figure 3. Overturning-resisting mechanism: frame and infills contributions.](image)

Given the amount of overturning moment resisted by the infills, the related base shear contribution is calculated according to Eq. 3, where \(H^*\) is the position of the resultant of the external forces that produces the same global over turning moment (Eq. 4, in which \(H_i\) is the height of the \(i^{th}\) level, measured from the foundation level). This \(H^*\) parameter, also measured from the foundation level, can be easily calculated for each step of the non-linear analysis, since the value of the external forces \(F_i\) is known.
Finally, if for each step the infills-related base shear is subtracted to the total base shear measured in the non-linear analysis, the frame base shear \( V_{b,rc} \) is obtained (Eq. 5) and the results of the analysis can be “disaggregated” or “decoupled” (Figure 4). It is worth reminding that, by definition, the frame contribution calculated in this way is different from the response of the original bare frame.

\[
V_{b,rc} = V_{b,tot} - V_{b,inf}
\]

It is worth mentioning that this decoupling procedure is valid regardless of the distribution of the infills, and it is applicable to multi-strut macro-models with straightforward modifications.

\[
V_{b,inf} = \frac{OTM_{inf}}{H^*}
\]

Where
\[
H^* = \frac{\sum_i F_i H_i}{\sum_i F_i}
\]

Figure 4. Disaggregation - or decoupling - of the frame and infills contributions to the base shear.

3. APPLICATION OF THE DECOUPLING PROCEDURE

In this Section, the proposed procedure is adopted to the interpretation of the pushover analysis results of simple models to show its suitability to decouple the contributions to the base shear from frame and infills. The numerical modelling strategy is first outlined and then calibrated against experimental results for a one-storey one-bay. Finally, a two-storeys one-bay frame, with bare, uniform or pilotis infill distributions, is adopted to demonstrate and validate the procedure.

3.1. Numerical modelling strategy

For each pushover analysis carried out for this paper, a displacement-control protocol (on the top storey) is adopted, applying a linear force profile and neglecting P-Delta effects. The non-linear FEM software Ruaumoko (Carr, 2016) was used for the calculations. Fixed boundary conditions are assumed at the base of the columns, together with rigid in-plane floor diaphragm constraint.

The numerical modelling strategy is summarised in Figure 5. Giberson mono-dimensional elements (Sharpe, 1974) are adopted for beams and columns, with the end cross-sections governed by a bi-linear Moment-Curvature relationship. The equivalent plastic hinge length is calculated according to Priestley et al., 2007. Joint panels are modelled by means of rigid arms. Therefore, their deformability is neglected.

Infill panels are modelled using a modified version of the typical single equivalent strut approach. In such refinement, the pinned ends of each strut are connected to the beam and column interfaces with the
joint panels by means of two rigid arms (one horizontal, one vertical) able to sustain axial load only (Figure 5). This allows to transfer the vertical and horizontal component of the axial load of the strut by means of shear demand for the beam and the column, respectively. When compared to the more commonly adopted method, in which the struts are connected to the centroid of the joints, this modified version allows to better capture the increase in shear demand in the beam-column joints (also shown in Figure 10). It is worth noting, however, that the distribution of the internal actions due to the infill-frame interaction as well as local effects, which are outside the scope of this paper, are not properly captured with this strategy as much as with a micro-modelling approach.

The strength of the equivalent struts was defined according to the formulations proposed by Bertoldi et al., 1993, which consider different failure mechanisms of the infill, including crushing at the centre or near the corners, sliding shear or diagonal tension. The struts are not able to sustain tension forces and the compression branch of their response is governed by the Axial Stress-Axial Strain relationship proposed in Crisafulli (1997).

3.2. Calibration against experimental results

The numerical parameters required for the model were calibrated against experimental results. In particular, a one-storey one-bay frame tested in the University of Pavia by Calvi and Bolognini (2001). The specimen is 3m tall and 4.8m long, with 0.3m x 0.3 m square columns and 0.7m x 0.25m beams. A clear cover of 30mm is provided for both the columns and the beam. Eight equally-spaced $\phi 22$mm bars are provided for the columns while the end sections of the beam are reinforced with $7 \phi 16$mm bars on the top of the section and $4 \phi 16$mm bars on the bottom. The infill wall is made of 120mm deep bricks with 60% void ratio, a vertical compression strength equal to 1.90MPa and a vertical elastic modulus equal to 1873MPa. A more detailed description of the specimen, together with the full list of the mechanical characteristics of the masonry, is reported in Calvi and Bolognini (2001).

Figure 6 shows the cyclic tests on the bare frame configuration (Test 1) and the infilled frame configuration (Test 2). In the same figure, the numerical pushover analysis conducted with the above-mentioned modelling strategy is shown. It is evident that the numerical curve is able to appropriately envelope the cyclic response, both for low and high displacement amplitudes. This is deemed to validate the adopted numerical modelling strategy.
3.3. Practical example

The proposed decoupling procedure is herein applied to the Pushover analysis of a two-storey one-bay benchmark frame presenting 3 different infills configurations (Figure 7): bare, uniformly infilled and pilotis. The geometrical and mechanical characteristics of the specimen described in Section 3.2 are used to generate this virtual case study. However, it is deemed that the specific characteristics of the frame are not fundamental, since the specific purpose of this example is to demonstrate the applicability of the proposed decoupling procedure.

The results of the pushover analyses are shown in Figure 8, highlighting the frame and infill coupled and decoupled contributions in each configuration. For this particular case studies, the detailing of the RC members allows, in both the pilotis and the uniform case, to engage the infills up to a drift level where their contribution vanishes and to finally develop a global mechanism in the frame.

The peak contribution of the infills to the base shear (Eq. 3, dash-dot lines in Figure 8) for the uniformly infilled case is approximately twice the analogous contribution in the pilotis case. This somehow indicates a proportionality between this parameter and the number of the infills, provided that the frame is not affected by any local failure mechanism (i.e. soft storey). This result is corroborated by an extensive parametric analysis for infilled frames conducted in Gentile (2017). Moreover, the peak of the infills contribution develops for different values of the top displacement, considering that the displaced shape causes different levels of engagement for the infills.
One remarkable result is that the frame contribution (Eq. 5) differs considerably from the response of the bare frame, and this effect is more pronounced in the pilotis case. Confirming what stated in Section 2, this is due to the “modified” force pattern $F_i$ (Eq. 1) fictitiously applied to the structure (Figure 2.c). In fact, the distribution of the infills plays a major role in the definition of the forces $F_i$. This is demonstrated in Figure 9, where the modified force pattern $F_i$ is calculated for the uniformly infilled and the pilotis cases, in correspondence to the peak contribution of the infills. Clearly, the presence of the infills at ground level creates a bypass for part of the force of the first level, directly transmitting it to the foundations.

Figure 9. Modified force pattern on the frame contribution schemes calculated at the peak response of the infills.

Finally, Figure 10 shows the shear diagram of the uniform and the pilotis cases, calculated in correspondence of the peak of the infills contribution (the related point on the capacity curves is indicated in Figure 9). In both cases, the results are compared to the bare frame shear diagrams, related to the same top displacement. The beam shear is not shown to improve the readability of the plot. By connecting the equivalent struts to the beams and columns interfaces (see Section 3.1), it is possible to observe the discontinuity in the shear diagram of the columns, which is basically a “bypass” action that reduces their shear demand considerably. Although this “bypass” action is captured by connecting the
struts in the joints centroids, the modelling strategy adopted in this work allows to more realistically consider the shear demand on the beam-column joints, which can be considerably higher than the column shear demand, as shown in Figure 10.

4. CONCLUSIONS

In this paper, a mechanically-based interpretation of the infill-to-frame interaction for single- or multi-strut macro models is given. This allows to decouple the contributions to the base shear of the frame and the infills, for any given top displacement. The procedure is based on the superposition principle, which is valid within a general step of a non-linear analysis. This decoupling procedure can be used to post-process the results of pushover or time-history numerical analyses. It can be adopted in simplified analytical approaches, such as SLaMA (Simple Lateral Mechanism Analysis), to derive the capacity curve of an infilled frame whilst capturing the proper internal actions (as done in Gentile, 2017). The mechanically-based decoupling procedure is firstly outlined. Therefore, the suitability of the decoupling procedure is demonstrated through its application to the Pushover analysis of a two-story one-bay frame with three different infill distributions: bare, uniformly infilled and pilotis (in which the infill at ground level is missing). The adopted numerical model is firstly calibrated against the experimental test of a one-bay one-level infilled frame.

The results of the conducted numerical analyses confirm that the Force-Displacement response (capacity curve) of the frame part within an infilled structure is considerably different from the response of an analogous bare frame, especially when the infill contribution is maximum. In an infilled frame subjected to a given force pattern, the frame contribution to the Force-Displacement can be interpreted as the response of a bare frame loaded with a force pattern which is different from the original one. The modified pattern embeds the horizontal components of the strut forces, and hence it changes at each step of the non-linear analysis depending on the axial loads in the equivalent struts. It is particularly influenced by the distribution and the strength of the infills.

REFERENCES


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