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# OUT OF PLANE CAPACITY OF INFILLS AFTER IN PLANE LOADING: A PREDICTION ANALITICAL MODEL

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## Abstract

*Earthquakes produce on infills In-Plane (IP) and Out-Of-Plane (OOP) actions. The recent earthquakes have proved that the OOP collapse of infills is a diffused mechanism also in buildings designed to resist to seismic events in agreement to the most modern strategies. This fact makes the question arises about the safety of infills with respect OOP actions. The strong interaction between IP and OOP behaviour of infills traduces in a progressively reduction of the OOP strength. Further, only in few cases codes suggest adequate strategies to face this issue. For what above, in the paper the reduction of OOP strength because of the IP damage is studied by an extended numerical experimental campaign based on FE models to be considered as complementary to the very few laboratory experimental tests available in the literature.*

**Keywords:** Infills, Out-of-Plane behaviour, In-Plane/Out-of-Plane interaction, Out-of-plane strength.

## 1 INTRODUCTION

In the last fifty years, the interaction between frame and infills deeply studied. Damage observed after earthquakes has highlighted the influence of infill panels on frames and the need to analyse in detail this phenomenon for a reliable assessment of buildings. A high number of studies refer to the in-plane (IP) behaviour (e.g. [1-12]). However, during earthquakes, the infills are subjected to out-of-plane (OOP) actions that frequently cause collapse. Further, the damage caused by IP actions reduces the OOP capacity of infills increasing the probability of OOP collapse with high risk for human health also in the case of building structures designed in agreement with the modern codes.

Different experimental studies have been carried out to observe the IP-OOP interaction. Dawe and Seah [13], Angel [14], Flanagan e Bennett [15]. Further, experimental studies were conducted by Komaraneni and Rai [16] and more recently Ricci et al [17]. A similar experimental campaign was carried out by Furtado et al [18]. Other tests can be found in [19-23].

Different codes face the problem of the OOP infills capacity (e.g. [24-26]). However, the need to have tools for the assessment of infilled frame structures of simple application has pushed different authors to modify the equivalent diagonal strut for the in-plane behaviour in such a way to assume a flexural behaviour suitable for the OOP behaviour. Different approaches have been proposed as explained in [26-32] that are the counterparts of much more classical strategies (e.g. [33-34]).

To date, the laws proposed for the reduction of the OOP capacity because of IP damage are based on very few tests. This study wants to increase the available data by a numerical experimentation and eventually to update the above laws. To this aim models have been formulated through the use of the Finite Element Method by using damage mechanical laws of the materials and an appropriate frame-infill interface as described in the next sections.

## 2 AVAILABLE OOP CAPACITY MODELS

The capacity models of infills subjected to OOP actions, under the hypothesis that the infill is in contact with the surrounding frame, are based on the arching action transmitted between frame and infill.

The arching actions and the dependence of the capacity on the compressive strength was first discussed by McDowell (1956) [19]. Dawe and Seah [13] developed a strength model based on virtual work concepts. The experimental studies carried out by them demonstrated a significant influence of the boundary conditions, in fact the infills everywhere in contact along the boundary with the frame had a capacity 4-5 times greater than others.

Bashandy et al. (1995) [35] extended the analytical method developed by McDowell et al. [19]. A simplification of the model by Angel [14] has been developed in FEMA 273 [25] and 356 [24].

The effect of the interaction between in-plane and out-of-plane responses is basic for a building safety assessment. First, experimental studies to recognize the IP-OOP interaction were carried out by Angel. (1994) [14]. As a result of the experimental campaign, the following out-of-plane capacity model was proposed:

$$q_u = 2\frac{f'_m}{\left(\frac{h}{t}\right)} \; R_1 R_2 \lambda \tag{1}$$

where λ is a term that includes the effect of the maximum masonry compressive stress, the maximum strain and the ratio between width and height of the panel, all quantities being related to the slenderness ratio, while $R_1$ and $R_2$ are reduction factors.
The expressions of coefficients $R_1$ and $R_2$ are:

$$R_1 = \left(1.08 + \left(\frac{h}{t}\right)\left\{-0.015 + \left(\frac{h}{t}\right)\left[-0.00049 + 0.000013\left(\frac{h}{t}\right)\right]\right\}\right)^{\Delta/2\Delta_{cr}} \tag{2}$$

$$R_2 = 0.357 + 2.49\times10^{-14}\,EI \leq 1.0 \tag{3}$$

and finally the expression for λ is

$$\lambda = 0.154\, e^{-0.0985(h/t)} \tag{4}$$

While the expression of $R_1$ proposed by Angel is proposed by FEMA 306 as well [23], differently, the guidelines for the seismic assessment of existing buildings in New Zeeland [36] suggest an expression for the reduction of the OOP strength not depending from the level of the in plane drift experienced, that is

$$R_1 = min\left(1.1\left(1 - \frac{h/t}{55}\right);1\right) \tag{5}$$

Eq. (5) is clearly justified by the difficulty to know which is the in plane drift experienced by an infill.

Recently, a stepwise formulation, for the IP/OOP interaction on the OOP strength for thin infills, has been proposed by Morandi et al. [37] that makes the effect of in plane damage start at an interstorey drift ratio (IDR) equal to 0.30%. Finally, after an experimental campaign, Ricci et al (2018) [17], not satisfied of the available models, tried to propose a new law of reduction of the OOP capacity because of IP damage. The tests, involving r.c. frames with brick masonry infills, led to the following capacity model:

$$R_1 = \left[min\left(1;0.14IDR^{-1.12}\right)\right] \tag{6}$$

where the interstorey displacement ratio has to be inserted in percentage. In this case a reduction of the strength of about 40% is reached when the in-plane drift reaches 0.3%.
The advantage of the above expressions with respect to that proposed by Angel is that there is not a dependence from the drift at the first cracking but only on the maximum IP drift experienced by the infill.
The comparison of the above models, included in Fig. 1, shows an affinity between the models by Morandi et al., Ricci et al. and Angel when the infill in-plane drift at the first cracking ($IDR_{cr}$) is 0.15 %. In the next section the numerical analysis of a number of infilled frames is carried out, loaded In Plane and Out of Plane, to be used as further data for a better definition of the OOP infill strength decaying curve of In-Plane damaged infills.

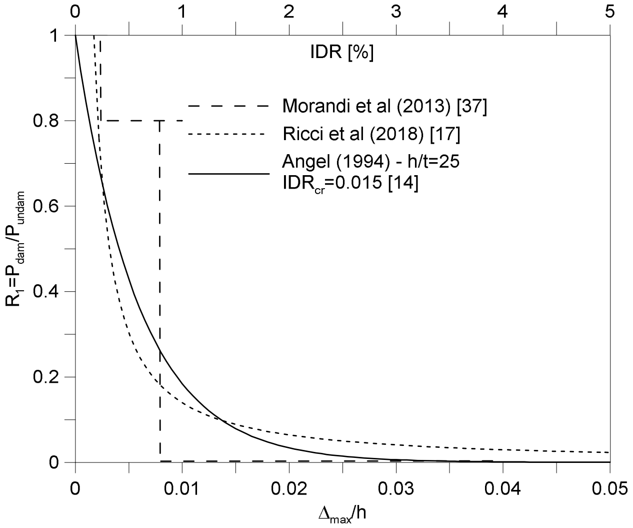

**Figure 1.** Comparison between OOP capacity reduction models.

# 3 RESULTS AND DECAY LAWS

## 3.1 Numerical analyses

Once the model was validated, a numerical study was carried out. Three different types of frames were considered able to contain infills with height respectively 2400 mm and 3600 mm. The geometric characteristics are inserted in Fig. 2.

Different types of masonry infills were studied having different thickness and different mechanical characteristics of the masonry. For each specimen different levels of the damage due to in-plane loading were caused before to be tested out-of-plane. The in-plane damage was obtained by making the infilled frames experience different levels of the drift during three loading cycles. In Tabs 1, 2 and 3 the specimens analyzed with the geometrical and mechanical characteristics of the infills and the frames are listed (the meaning of the symbols is obvious).

| | characteristics of infill material in compression (CDP model) | | | | | infill geometry | | | |
|---|---|---|---|---|---|---|---|---|---|
| **model** | **$E_0$** [Mpa] | **$\sigma_{mc}$** [Mpa] | **$\varepsilon_{mc}$** | **$\sigma_{mcu}$** | **$\varepsilon_{mcu}$** | **h/t** | **t** [mm] | **h** [mm] | **in-plane drift** **($\Delta_{ip}$)** [%] |
| 4 | 3000 | 3 | 0.002 | $0.1\sigma_{mc}$ | 0.004 | 24 | 100 | 2400 | 0 0.1 0.35 0.5 1 2 |
| 5 | | | | | | 12 | 200 | | |
| 6 | | | | | | 8 | 300 | | |
| 10 | 3000 | 3 | 0.002 | $0.1\sigma_{mc}$ | 0.004 | 36 | 100 | 3600 | 0 0.1 0.35 0.5 1 2 |
| 11 | | | | | | 18 | 200 | | |
| 12 | | | | | | 12 | 300 | | |

**Table 1.** Properties of the numerical models and damage assigned

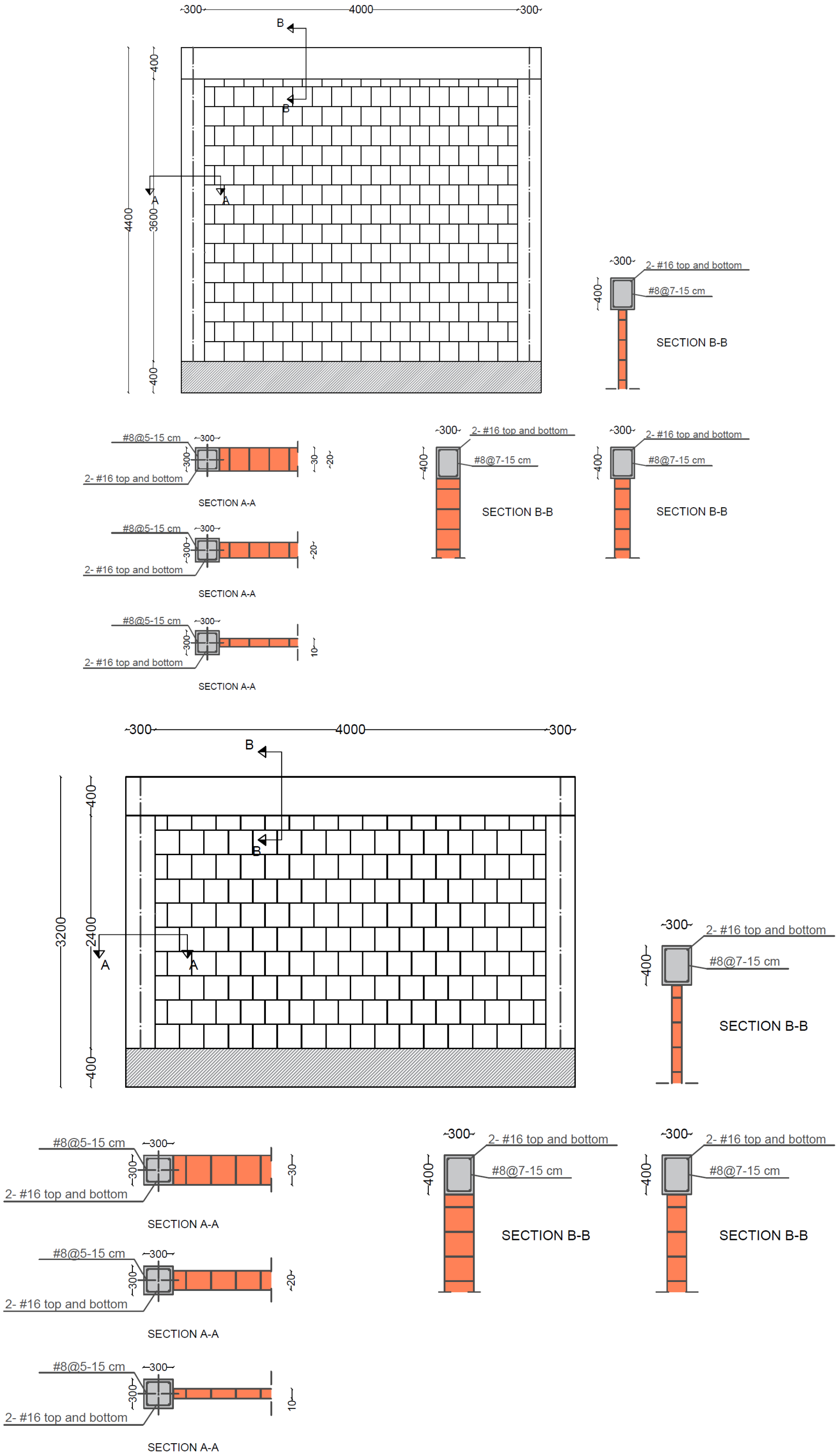

**Figure 2.** Geometric characteristics of infilled frames considered for the numerical analyses.

| | characteristics of infill material in tension (CDP model) | | | | frame geometry | | characteristics of concrete in compression (CDP model) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **model** | **$E_0$** [Mpa] | **$\sigma_{mt}$** [Mpa] | **$\varepsilon_{mt}$** | **$\varepsilon_{tu}$** | **beam** [cmxcm] | **column** [cmxcm] | **$E_0$** [Mpa] | **$\sigma_{mc}$** [Mpa] | **$\varepsilon_{mc}$** | **$\sigma_{mcu}$** | **$\varepsilon_{mcu}$** |
| 4 | 3000 | $0.05\sigma_{mc}$ | $\sigma_{mt}/E_0$ | $4\varepsilon_{mt}$ | 30x40 | 30x30 | 20000 | 25 | 0.002 | $0.65\sigma_{mc}$ | 0.008 |
| 5 | | | | | | | | | | | |
| 6 | | | | | | | | | | | |
| 10 | 3000 | $0.05\sigma_{mc}$ | $\sigma_{mt}/E_0$ | $4\varepsilon_{mt}$ | 30x40 | 30x30 | 20000 | 25 | 0.002 | $0.65\sigma_{mc}$ | 0.008 |
| 11 | | | | | | | | | | | |
| 12 | | | | | | | | | | | |

**Table 2.** Properties of the infill materials in tension and of concrete in compression

| | characteristics of concrete in tension (CDP model) | | | | characteristics of steel rebars (elastic perfectly plastic model) | |
|---|---|---|---|---|---|---|
| **model** | **$E_0$** [Mpa] | **$\sigma_{mt}$** [Mpa] | **$\varepsilon_{mt}$** | **$\varepsilon_{tu}$** | **$E_s$** [Mpa] | **$\sigma_y$** [Mpa] |
| 4 | 20000 | $0.2\sigma_{mc}$ | $\sigma_{mt}/E_0$ | $4\varepsilon_{mt}$ | | |
| 5 | | | | | | |
| 6 | | | | | | |
| 10 | 20000 | $0.2\sigma_{mc}$ | $\sigma_{mt}/E_0$ | $4\varepsilon_{mt}$ | | |
| 11 | | | | | | |
| 12 | | | | | | |

**Table 3.** Properties of the concrete in tension and of steel rebars

Each test was displacement controlled. In Fig. 3 a response due to in-plane loading is shown. The out-of-plane loading allowed to recognize the loosing of strength because of in-plane damage. In Fig. 4 some responses obtained by the FE analysis are inserted showing clearly a progressive reduction of strength for increasing in-plane damage.

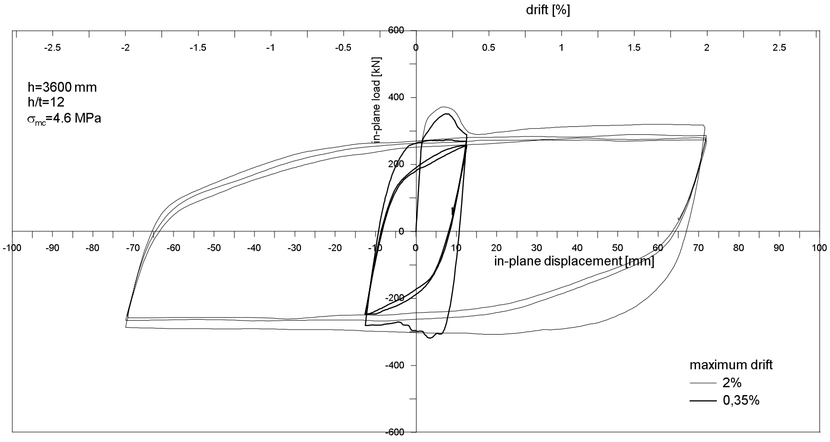

**Figure 3.** In-plane loading cycles characterized by different maximum drifts.

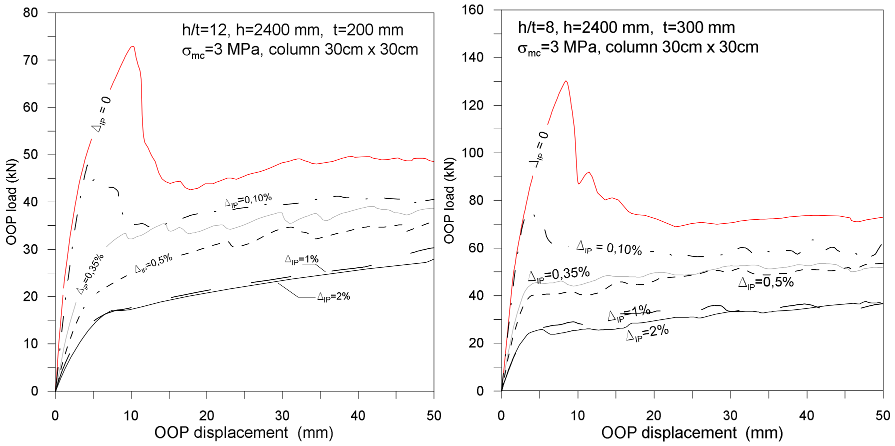

**Figure 4.** Some OOP infill response

## 3.2 OOP strength decays

From each curve of the type inserted in Fig. 4 the peak of strength was evaluated. Then, the decaying in the strength due to the damage produced by the in-plane loading was calculated. Considering the characteristics of the OOP load – OOP displacements curves, the peak of strength was obtained conventionally in correspondence of a strong variation (reduction) of the tangent stiffness.

Note that the hardening in each curve after the peak strength is the consequence of the arch effect perfectly reproduced by the FE model. This effect has not been always exhibited in the experimental tests probably for the low effectiveness of the infill surrounding supports (for example, the tests by Ricci et al. [17], do not highlight any hardening).

In Fig. 5 the numerical results obtained by the study here described and the (few) experimental results available in the literature are collected in terms of OOP strength decay ratio versus IP damage. The figure in question shows that the experimental results are in the cloud of the numerical results. If the results are differentiated associating at each of them the infill shape ratio h/t it is not possible to recognize a clear trend of the OOP strength decay depending on h/t. This fact is in contrast with the approach used by Angel - see Eq.2– that proposes a strong dependence on h/t. But this result validates the simpler approaches of Ricci et al. and Morandi et al. that are not dependant on the infill shape ratio h/t.

To this point a comparison of the experimental and numerical results with the models proposed by Ricci et al. and by Morandi et al. highlights that (observe Fig. 6 where the experimental results proposed in [38] are also included), while the model proposed by Morandi et al. is strongly not conservative between an IP damage, expressed in terms of IP drift, in the range 0%-1%, the model proposed by Ricci et al. is a good alternative, although it has been defined referring only to a low number of the experimental results.

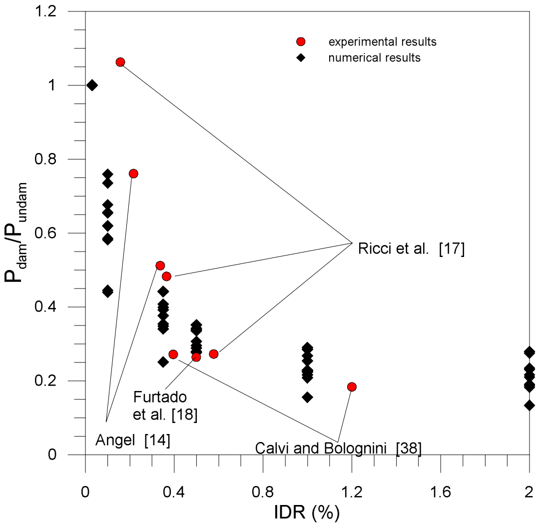

**Figure 5.** Reduction of OOP strength versus IP damage: experimental and numerical results

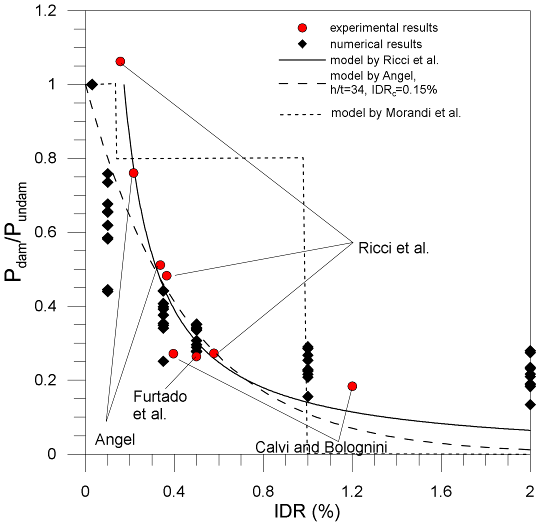

**Figure 6.** Reduction of OOP strength versus IP damage: experimental and numerical results compared with the available models

Nevertheless, the model provided by Ricci et al. underestimates the mean loss of OOP strength for the IP drifts between 0% and 0.5 % and overestimates the loss of OOP strength for the IP drifts between 0.5 % and 2%. The overestimation of the loss of strength is evident both comparing the model proposed with the experimental and the numerical results.

In Fig. 7 the lower bound curve, the curve fitting the results, the model by Ricci et al. and the experimental and numerical results are inserted. The lower bound curve and the fitting curve can be considered as two updated tools for the prediction of the OOP strength of infills that have experienced in-plane actions.

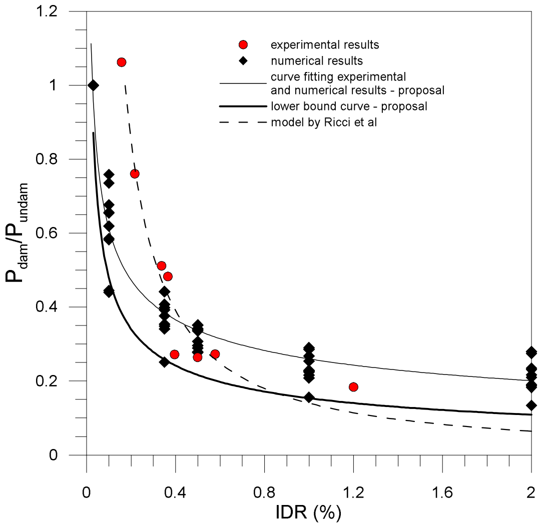

**Figure 7.** Reduction of OOP strength versus IP damage: experimental and numerical results compared with the proposed models

The equations of the proposed curve fitting the experimental and numerical results is

$$F_f = \left[ min\left( 1;0.26\, IDR^{-0.37} \right) \right] \tag{7}$$

while the equation of the proposed lower bound curve is

$$F_{lb} = \left[ min\left( 1;0.15\, IDR^{-0.49} \right) \right] \tag{8}$$

The lower bound curve matches well the model of Ricci et al. after an IDR of 0.7% is reached.

## 4 CONCLUSIONS

In this paper the interaction IP-OOP behaviour of infills has been discussed starting from the strategies today available to predict the OOP response. The analysis of the literature highlights that the above prediction models are based on very few experimental tests, namely these models are not enough supported by real observations. For this reason, the paper provides a numerical analysis campaign based on FE models involving a number of infills with surrounding frames with different geometrical and mechanical characteristics in order to obtain data for a better definition of the decaying law for the OOP strength of infills to be used for the practical applications. The numerical investigation has shown that:

1) the models of the OOP infill capacity, at the moment available and based on very few experimental investigations, need to be improved;
2) the decaying of out-of-plane strength is strongly influenced by the damage undergone by infills because of in-plane loading and it is never negligible, not even for low IP drifts;
3) conversely of what proposed by Angel [14], the numerical investigation here discussed and the experimental data available in the literature show that there is not a

clear dependence of the decay of infill OOP strength on the shape ratio (height *h* divided by width *t*); this observation is consistent with some of the approaches in the literature (e.g. Ricci et al. [17], Morandi et al [37]);

4) an updated model for the decaying of strength has been proposed in this paper fitting the data obtained by the numerical investigation carried out during this study and the data available in the literature from the laboratory tests;
5) also, a model for the lower bound OOP strength of infills has been proposed depending on the damage due to IP loading;
6) the proposed models update the available models in the sense of a more reliability of the prediction.

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