

Article

On the Out-of-Plane Strength of Masonry Infills Encased in RC Frames

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Featured Application

The out-of-plane (OOP) failure of infill walls during major earthquakes can cause both human casualties and reduction in the seismic resistance of buildings. This paper reviews the available experimental and analytical studies from the literature on the OOP capacity of unreinforced masonry (URM) infills without openings, enclosed in reinforced concrete (RC) frames. A comprehensive database of pseudo-static tests on the sequential in-plane (IP) and OOP loadings of infills is presented. The predictive performances of existing models for OOP strength are evaluated, and improved formulas are proposed to capture the effect of prior IP drift on the OOP capacity, reflecting vulnerability characteristics identified in tests. The detrimental influence of gaps between infills and RC frames is also discussed.

Abstract

With reference to the widespread out-of-plane (OOP) failures of infill walls in reinforced concrete (RC) buildings during the 6 February 2023 earthquakes in Kahramanmaraş, Turkey, this paper investigates the OOP strength of unreinforced masonry (URM) infills without openings, enclosed in RC frames, while also considering the effect of prior in-plane (IP) loading. A comprehensive database has been compiled, including all available tests on infills subjected to OOP loading and sequential IP–OOP loading, as well as those on infills with gaps between the RC frame and the masonry panel. This study evaluates the effectiveness of established design models at predicting the OOP strength of infills in RC frames and proposes refinements to improve the predictive accuracy. For the OOP strength, two arch-based models are applied, and the impact of prior IP loading is addressed through a reduction factor, R . Based on test observations showing that prior IP loading disproportionately reduces the OOP strength in vulnerable infills, an improved R -factor is introduced, providing better alignment with experimental results than four existing design formulas. The influence of gaps between the infill and RC frame on the OOP behavior is also examined. The findings reveal inconsistencies and reduced reliability among the available design models, highlighting the need for further research on this critical topic.

Keywords: masonry infills; OOP strength of infills; prior IP-damaged infills; gapped infills; capacity models; experimental database



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1. Introduction

Infill walls, although considered non-structural elements, significantly increase the in-plane elastic stiffness and strength of reinforced concrete (RC) frames and may contribute substantially to the earthquake resistance of RC buildings [1,2]. However, irregularities in

the layout of masonry infills—either in elevation or in plan—have been shown to cause severe damage or even building collapse during major earthquakes [3–5]. Infills, typically constructed of hollow clay or concrete units or lightweight solid blocks, have limited deformation capacity and tend to fail in a brittle manner. Failure of infill walls at the early stages of an earthquake often leads to an increased displacement demand and the shear overloading of RC columns [6–8], as well as additional torsional irregularities [9,10], which may result in severe structural damage or collapse.

During seismic excitation, masonry infills in RC buildings are subjected to both in-plane (IP) and out-of-plane (OOP) actions. In-plane displacements can damage the infill and weaken its connection to the surrounding RC elements. If the infill is subsequently subjected to OOP loading, its strength and stiffness are reduced compared with those of an undamaged infill, e.g., [11–15]. The capacity of infills to resist OOP inertia forces depends primarily on the extent of prior IP damage, the slenderness (height-to-thickness) ratio, and the boundary conditions between the infill and surrounding RC frame [16]. Infills with strong boundary restraints along all four sides generally demonstrate the highest OOP strengths [17,18]. Infills connected to the RC elements only at their upper and lower edges [19,20], or those connected only at the top and bottom edges [19,20] or along three edges, leaving a gap at the top [21,22], exhibit significantly reduced OOP strengths.

The motivation for this work stems from the widespread OOP failures of infill walls observed in RC buildings during the 6 February 2023 Kahramanmaraş earthquakes in Turkey, which resulted in more than 50,000 fatalities [10,23,24]. In many cases, external infills were inadequately connected to the RC frames. Moreover, gaps were frequently observed between the tops of the infills and the upper RC beams, which triggered OOP failure (Figure 1). Similar gaps were also documented in infills constructed in architectural overhangs, commonly encountered in buildings in Turkey. The seismic responses of such configurations likely enlarged the gaps between the infills and RC structures during shaking, ultimately precipitating OOP failure (Figure 1c).

There is broad consensus that the brittle failure of infill walls is highly undesirable [25], and both analytical and experimental studies have addressed this issue. In different parts of the world, different provision practices are followed for infills and, hence, research is oriented to address or improve these specific construction practices, for example, in China [26,27], among others.

This paper focuses on unreinforced masonry infills without openings, enclosed in RC frames, and without mechanical devices or other reinforcement connecting the infill to the frame. This study examines two key factors that likely contributed to the OOP failures of masonry infills during the 2023 Kahramanmaraş earthquakes:

- (a) The effect of prior IP loading on the OOP capacity (IP–OOP interaction);
- (b) The effect of gaps between the infills and RC frames (gapped infills).

To this end, a database has been compiled including all available pseudo-static tests on infills subjected to sequential IP–OOP loading. Shake-table tests are not included due to their scarcity [16,19] and inconsistent results compared with pseudo-static tests.

This study also evaluates the predictive accuracy of established design models in estimating the OOP strength of infills, with the aim of improving design procedures. The OOP strength is first assessed using two arch-based models (Dawe and Seah [28]; Ricci et al. [29]), whose limitations are discussed. The effect of prior IP loading is incorporated through a reduction factor, R . Based on test data, an improved R -factor is proposed, with distinct formulations for vulnerable and non-vulnerable infills. This new factor yields the most accurate predictions of experimental results compared with four existing formulas.



Figure 1. Failure of infills not well encased in the structure: (a,b) infills built exterior to the RC structural elements, (c) exterior infills built between slabs in overhangs, and (d) interior infills with a gap along the infill perimeter and RC members also without connection between the two leaves of bricks.

Section 2 summarizes the analytical background and design equations evaluated in this study. Section 3 describes the experimental studies and the database of fully bounded specimens. Section 4, based on the database, discusses the predictive capacity of the design models and presents an improved design methodology for the IP–OOP capacity of fully bounded infills. The performance of gapped infills is discussed in Section 4.3, and their properties are given in Table 8.

2. Out-of-Plane (OOP) Capacity of Masonry Infills

2.1. General Aspects of OOP Behavior

The out-of-plane (OOP) capacity of infill panels in tests is defined as the uniform lateral pressure applied over the surface of the panel that leads to collapse. The boundary conditions between the infill and the surrounding frame influence both the crack pattern and the OOP strength [16,30]. Infills fully supported along all four edges tend to develop horizontal and diagonal cracks at approximately 45° , extending toward the corners of the supports. Different boundary conditions lead to different crack patterns. At early loading stages, infills behave as elastic plates. Figure 2a,b show idealized flexural crack patterns for panels fully connected on four sides and for those with a gap at the top beam, respectively [31]. When infill walls are well confined within RC frames that are significantly stiffer and stronger than the masonry, load transfer occurs through strut mechanisms after flexural cracking, commonly referred to as the arching effect [32,33]. This mechanism involves hinges at the top and bottom of the panel and an intermediate hinge at mid-height. The arching effect, which relies on the compressive strength of the infill, explains the higher OOP capacity observed in tests [34,35], compared with pure flexural behavior,

which depends on tensile strength [28]. If the panel is adequately connected along all four sides (4E), a bi-directional arching mechanism is expected (Figure 2a). In panels connected only along the horizontal edges (2E), only vertical arching may be activated. In three-edge-supported (3E) panels, with a small gap at the top, uni-directional arching is expected; however, tests show that rocking at the base may close the top gap, enabling a bi-directional mechanism (Figure 2b) [16]. Arching requires sufficient thickness to prevent premature disintegration or rocking failure [16,36]. Failure typically occurs through crushing at the arch thrust zones. Potential arch mechanisms for the infills in Figure 2 are indicated by dashed lines.

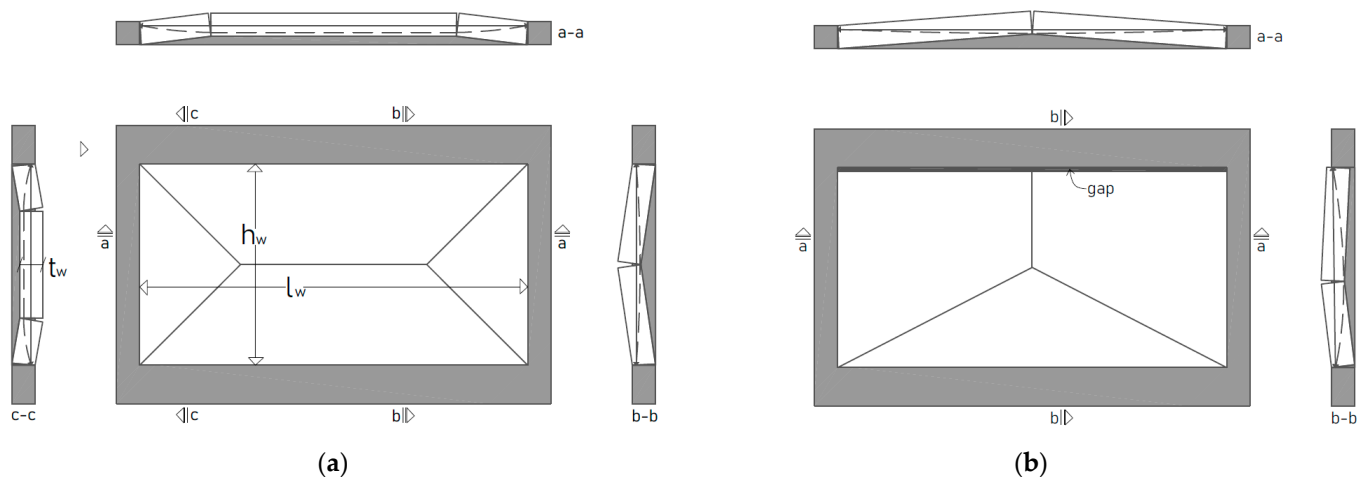


Figure 2. Idealized flexural crack pattern of infills because of OOP loading and subsequent arch mechanism for infills connected to the RC frame (a) along four edges and (b) along three edges due to a gap between the infill and upper beam.

Experimental studies confirm that the arching contribution depends strongly on the infill aspect ratio, h_w/l_w , where h_w and l_w are the height and length of the infill [37,38]. For a given infill height, lower aspect ratios result in reduced OOP strength [39]. Square panels ($h_w/l_w \approx 1$) develop stronger arching action because arching tends to form along the shorter side [40,41].

The contribution of arching also increases with the compressive strength [42,43] and is influenced by the orientation of the holes in hollow bricks. Tests by Di Domenico et al. [44] showed that vertical arching perpendicular to bricks' holes produced brittle failure, whereas horizontal arching parallel to the holes led to more ductile post-peak behavior.

Prior in-plane (IP) actions reduce the OOP strength by degrading the frame–infill connection and creating cracks in the panel [45]. The extent of this reduction depends on the imposed IP drift and the geometric properties of the wall, as discussed in the following sections.

2.2. Design Models for OOP Capacity

2.2.1. Infills Without Prior IP Damage

The first one-way arch model for OOP strength was proposed by McDowell et al. (1956) [46] and consists of a three-hinge arch. Reviews of such models are available in [30] and elsewhere. Comparative assessments of the existing formulas can be found in [44,47]. Among the many proposed formulas, this study considers two: (a) that of Dawe and Seah (1989) [28] and (b) that of Ricci et al. (2018a) [29], selected because of their good predictions and simplicity, respectively. The New Zealand Guidelines [48] adopt the Dawe and Seah model.

Dawe and Seah [28], based on tests on infills with hollow concrete blocks in steel frames, were the first to propose an empirical model accounting for the two-way arch mechanism for the OOP strength, q_u (in kPa), of masonry infills bounded to the confining frame along four edges, or along three edges with a gap between the infill and top beam, according to Equations (1) and (2), respectively. The effect of vertical arching on the OOP resistance of the infill is expressed by variable β in Equation (4). The effects of horizontal arching on the OOP strength are described by variables α and α_{gap} from Equations (3) and (5) in the cases of fully supported and gapped infills, respectively. The model considers the geometrical properties of the frame members and was calibrated on the authors' tests on infilled pinned steel frames. Hence, it tends to underestimate the OOP strength in RC moment-resisting frames [44,47]:

$$q_u = 800 \times (f_w)^{0.75} \times t_w^2 \times \left(\frac{\alpha}{l_w^{2.5}} + \frac{\beta}{h_w^{2.5}} \right) \quad (1)$$

$$q_u = 800 \times (f_w)^{0.75} \times t_w^2 \times \left(\frac{\alpha_{gap}}{l_w^{2.5}} \right) \quad (2)$$

$$\alpha = \frac{1}{h_w} \times (E_c \times I_c \times h_w^2 + G_c \times J_c \times t_w \times h_w)^{0.25} \leq 50 \quad (3)$$

$$\beta = \frac{1}{l_w} \times (E_c \times I_b \times l_w^2 + G_c \times J_b \times t_w \times l_w)^{0.25} \leq 50 \quad (4)$$

$$\alpha_{gap} = \frac{1}{h_w} \times (E_c \times I_c \times h_w^2 + G_c \times J_c \times t_w \times h_w)^{0.25} \leq 75, \quad (5)$$

where f_w is the compressive strength of the masonry infill (in MPa), which is determined from the compressive strength of the infill along the infill direction for which the prevalent arch mechanism is expected to be activated (i.e., f_{wv} for vertical arching, and f_{wh} for horizontal arching); l_w and h_w are the length and the height of the infill wall (in mm); t_w is the infill thickness (in mm), limited by the authors to one-eighth of the infill height ($t_w \leq h_w/8$); E_c and G_c (in MPa) are the Young's modulus and shear modulus of the materials of the RC frame, respectively; I_c and I_b (in mm⁴) are the moments of inertia of the confining columns and beams; J_c and J_b (in mm⁴) are the torsional constants of the columns and beams, respectively.

Equation (6) by Ricci et al. [29], while simple, has been shown to provide accurate predictions (e.g., [47]). It was calibrated on the test results of Angel et al. [49], Flanagan and Bennett [50], Calvi and Bolognini [51], Hak et al. [52], and Furtado et al. [45]:

$$q_u = 1.95 \times f_w^{0.35} \times \frac{t_w^{1.59}}{h_w^{2.96}}, \quad (6)$$

where f_w is the compressive strength of the masonry infill (in MPa), t_w and h_w are the thickness and height of the infill wall (in meters), and q_u is the OOP strength (in MPa).

2.2.2. Infills with Prior IP Damage

When an infill has experienced IP drift, its OOP capacity is reduced. This reduction is typically represented by a factor, R , defined as the ratio of the IP–OOP strength to the OOP strength of an undamaged panel. Several equations for R exist. Four widely cited ones are considered below and in Table 1.

Di Domenico et al. (2021) [53] proposed Equation (7), which was demonstrated in [47] to have the best predictive capacity among 12 similar models. Equation (7) is applicable only to infill walls with l_w/h_w values between 1 and 1.6, with h_w/t_w values higher than 8, and for IDR demands lower than 1.2%. Ricci et al. [54], based on six tests on infills with h_w/t_w values of 22.9 and 15.3 (thicknesses of 8 and 12 cm, respectively) proposed

Equation (8) to calculate the reduction factor (R). The same researchers, in addition to their own six tests, based on the experimental results of Angel et al. [49], with $h_w/t_w = 34.1$, and Calvi and Bolognini [51], with $h_w/t_w = 20.4$, reached the conclusion that the slenderness ratio, h_w/t_w , affects the R -factor only when it is lower than 20. Hence, they proposed Equation (9) as an alternative to Equation (8). It is noted that Equations (7)–(9) introduce a lower limit equal to 1, so that in case the formula results in higher R values, an R value of 1 is assumed; i.e., there is no reduction in the OOP strength because of prior IP loading.

Furtado et al. [43] proposed Equation (10) for the calculation of the OOP strength and stiffness reduction, both at cracking and peak load. In Equation (10), the R -factor is related only to the value of the IP drift (IDR) prior to the OOP loading. The expression was derived based on the test results of Angel et al. [49], Calvi and Bolognini [51], Furtado et al. [45], and Ricci et al. [29].

Table 1. Predictive equations for R -factor.

References	Equations	
Di Domenico et al. [53]	$R = \min\left\{1; \left((1.51 - 0.19 \times \frac{l_w}{h_w} - 0.05 \times \min(\frac{h_w}{t_w}; 20.4)) \times IDR^{-0.73}\right)\right\}$	(7)
Ricci et al. [54]	$R = \min\left\{16.7 \times IDR^{-0.69} \times \left(\frac{h_w}{t_w}\right)^{-1.36}; 1\right\}$	(8)
Ricci et al. [54]	$R = \min\left\{\left(0.98 - 0.04 \times \min(20.4; \frac{h_w}{t_w})\right) \times IDR^{-0.97}; 1\right\}$	(9)
Furtado et al. [43]	$R = 0.1638 \times IDR^{-0.946}$	(10)

Note: R is the OOP strength reduction factor of the masonry infill; l_w , h_w , and t_w are the length, height, and thickness of the infill, respectively; IDR is the in-plane drift ratio in %, to which the infill was subjected prior to OOP loading.

3. Experimental Database

All available experimental results, to the best knowledge of the authors, on unreinforced masonry (URM) walls without openings, enclosed in RC frames, and subjected to pseudo-static OOP loading have been compiled into a database. The ranges of the geometric and material properties are summarized in Table 2.

Table 2. Ranges of specimen characteristics included in the database.

Values	l_w (cm)	h_w (cm)	t_w (cm)	h_w/t_w	l_w/h_w	f_{wv} (MPa)	f_{wh} (MPa)	q_{exp} (kPa)	f_b (MPa)	f_m (MPa)
Min	135	98	4.8	8.4	1	0.53	1.08	0.52	1.6	2.8
Max	422	295	35	34.1	1.83	11.51	4.63	66.30	24.0	17.6

Note: l_w is the infill's length; h_w is the infill's height; t_w is the infill's thickness; f_{wv} , f_{wh} are the compressive strength of the infill in the vertical and horizontal directions, respectively; q_{exp} is the experimental out-of-plane strength of the infill; f_b is the compressive strength of the units; f_m is the compressive strength of the mortar.

Tables 3 and 4 display the specimen properties for the experimental studies in chronological order [45,49,51–62]. Generally, each study included a reference specimen tested only under OOP loading, and one to three companion specimens of identical properties first subjected to a maximum in-plane drift ratio (IDR) ranging from 0.15% to 2.71%, followed by OOP loading to failure (IP–OOP sequence). Some studies provided only IP–OOP tests without a reference OOP test (e.g., [52,62]; specimen 6b in [49]). These are still included, given the scarcity of data, and are used only to assess the accuracy of the theoretical IP–OOP infill strength (Section 4.2.2).

Table 3. Properties of RC frame members and loading characteristics.

Experimental Study	Specimen Name	Column Section (cm)	Beam Section (cm)	f_c (MPa)	E_c (GPa)	Loading	OOP Load Appl. ^a	IP Drift (IDR) (%)	OOP Drift (%)
Milijaš et al. [55]	T1	25/25	25/45	C30/37	32.84 ^c	OOP	abg	—	0.71
	T2	25/25	25/45	C30/37	32.84 ^c	IP–OOP	abg	1.20	1.46 ^d
Di Domenico et al. [53]	120S–OOP	27/20	27/20	42.9	34.05 ^c	OOP	4 pts	—	0.74
	120S–IPM–OOP	27/20	27/20	42.9	34.05 ^c	IP–OOP	4 pts	0.69	1.15
	120S–IPH–OOP	27/20	27/20	42.9	34.05 ^c	IP–OOP	4 pts	1.03	3.07
De Risi et al. [56]	OOP	27/20	27/20	42.9	34.05 ^c	OOP	4 pts	—	0.65
	IPL–OOP	27/20	27/20	42.9	34.05 ^c	IP–OOP	4 pts	0.15	1.14
	IPM–OOP	27/20	27/20	42.9	34.05 ^c	IP–OOP	4 pts	0.28	1.41
	IPH–OOP	27/20	27/20	42.9	34.05 ^c	IP–OOP	4 pts	0.51	1.97
Akhoundi et al. [57]	SIF–O–1L–B	16/16	27/16	C20/25	29.96 ^c	OOP	abg	—	2.96 ^d
	SIF–IO (0.3)	16/16	27/16	C20/25	29.96 ^c	IP–OOP	abg	0.30	3.00 ^d
	SIF–IO (0.5)	16/16	27/16	C20/25	29.96 ^c	IP–OOP	abg	0.50	6.16 ^d
	SIF–IO (1.0)	16/16	27/16	C20/25	29.96 ^c	IP–OOP	abg	1.00	7.37 ^d
Ricci et al. [54]	120_OOP_4E	27/20	27/20	46.2	34.82 ^c	OOP	4 pts	—	0.87
	120_IP + OOP_L	27/20	27/20	46.2	34.82 ^c	IP–OOP	4 pts	0.21	1.06
	120_IP + OOP_M	27/20	27/20	46.2	34.82 ^c	IP–OOP	4 pts	0.50	2.87
	120_IP + OOP_H	27/20	27/20	46.2	34.82 ^c	IP–OOP	4 pts	0.89	3.46
Di Domenico et al. [58]	OOP_4E	27/20	27/20	36.0	32.31 ^c	OOP	4 pts	—	0.59
	IP + OOP_L	27/20	27/20	36.0	32.31 ^c	IP–OOP	4 pts	0.16	0.74
Ricci et al. [59]	IP + OOP_M	27/20	27/20	36.0	32.31 ^c	IP–OOP	4 pts	0.37	3.50
	IP + OOP_H	27/20	27/20	36.0	32.31 ^c	IP–OOP	4 pts	0.58	2.82
Sepasdar [60]	IF–ND	18/18	18/18	35.8	16.91	OOP	abg	—	2.55
	IF–D1	18/18	18/18	35.8	16.91	IP–OOP	abg	0.66	1.35
	IF–D2	18/18	18/18	36.6	20.36	IP–OOP	abg	2.71	2.02
Wang [61]	IF–RC–ID	18/18	18/18	35.8	16.91	IP–OOP	abg	1.37	1.57
Furtado et al. [45]	Inf_02	30/30	50/30	26.8	24.70	OOP	abg	—	1.13 ^d
	Inf_03	30/30	50/30	26.8	24.70	IP–OOP	abg	0.50	0.11 ^d
Calvi & Bolognini [51]	10	30/30	25/70	25.0	31.48 ^c	OOP	4 pts	—	0.39 ^d
	2	30/30	25/70	25.0	31.48 ^c	IP–OOP	4 pts	1.20	—
	6	30/30	25/70	25.0	31.48 ^c	IP–OOP	4 pts	0.40	1.37 ^d

Table 3. Cont.

Experimental Study	Specimen Name	Column Section (cm)	Beam Section (cm)	f_c (MPa)	E_c (GPa)	Loading	OOP Load Appl. ^a	IP Drift (IDR) (%)	OOP Drift (%)
Angel et al. [49]	1	31/31	31/25	55.16	36.72 ^c	OOP	abg	—	1.40 ^d
	2b	31/31	31/25	55.16	36.72 ^c	IP–OOP	abg	0.34	2.50 ^d
	3b	31/31	31/25	55.16	36.72 ^c	IP–OOP	abg	0.22	1.80 ^d
Hak et al. [52]	TA1	35/35	35/35	30.00 ^b	30.59 ^c	IP–OOP	m	1.50	4.16 ^d
	TA2	35/35	35/35	30.00 ^b	30.59 ^c	IP–OOP	m	2.50	4.77 ^d
	TA3	35/35	35/35	30.00 ^b	30.59 ^c	IP–OOP	m	1.00	1.95 ^d
Da Porto et al. [62]	URM-D	30/30	25/50	30.00 ^b	30.59 ^c	IP–OOP	4 pts	0.50	1.82
	URM-U	30/30	25/50	30.00 ^b	30.59 ^c	IP–OOP	4 pts	1.20	2.63
Angel et al. [49]	6b	31/31	31/25	55.16	36.72 ^c	IP–OOP	abg	0.25	2.90 ^d

^a OOP load type: abg: airbag; 4 pts: 4 points; m: applied at the mid-height of the infill; ^b assumed values; ^c estimated from Equation (11); ^d value estimated from OOP force–displacement diagram by CAD tool.

Table 4. Properties of masonry infills (bounded at four sides to the RC frame).

Experimental Study	Specimen Name	Unit	l_w (cm)	h_w (cm)	t_w (cm)	f_{wv} (MPa)	f_{wh} (MPa)	q_{exp} (kPa)
Milijaš et al. [55]	T1	cbvh	277	252	30	2.40	—	25.16
	T2	cbvh	277	252	30	2.40	—	12.89
Di Domenico et al. [53]	120S-OOP	cbhh	183	183	12	1.29	1.64	9.94
	120S-IPM-OOP	cbhh	183	183	12	1.29	1.64	6.90
	120S-IPH-OOP	cbhh	183	183	12	1.29	1.64	6.00
De Risi et al. [56]	OOP	cbhh	183	183	8	2.37	4.63	8.80
	IPL-OOP	cbhh	183	183	8	2.37	4.63	9.39
	IPM-OOP	cbhh	183	183	8	2.37	4.63	6.72
	IPH-OOP	cbhh	183	183	8	2.37	4.63	5.74
Akhoundi et al. [57]	SIF-O-1L-B	cbhh	241.5	164	8	1.17	—	10.05
	SIF-IO (0.3)	cbhh	241.5	164	8	1.17	—	8.58
	SIF-IO (0.5)	cbhh	241.5	164	8	1.17	—	6.67
	SIF-IO (1.0)	cbhh	241.5	164	8	1.17	—	5.13
Ricci et al. [54]	120_OOP_4E	cbhh	235	183	12	1.65	2.12	9.74
	120_IP + OOP_L	cbhh	235	183	12	1.65	2.12	9.67
	120_IP + OOP_M	cbhh	235	183	12	1.65	2.12	6.49
	120_IP + OOP_H	cbhh	235	183	12	1.65	2.12	5.37

Table 4. Cont.

Experimental Study	Specimen Name	Unit	l_w (cm)	h_w (cm)	t_w (cm)	f_{wv} (MPa)	f_{wh} (MPa)	q_{exp} (kPa)
Di Domenico et al. [58]	OOP_4E	cbhh	235	183	8	1.80	2.21	5.12
Ricci et al. [59]	IP + OOP_L	cbhh	235	183	8	1.81	2.45	5.44
	IP + OOP_M	cbhh	235	183	8	1.81	2.45	2.44
	IP + OOP_H	cbhh	235	183	8	1.81	2.45	1.37
Sepasdar [60]	IF-ND	cmu	135	98	9	9.40	—	66.30
	IF-D1	cmu	135	98	9	9.70	—	44.40
	IF-D2	cmu	135	98	9	9.70	—	26.40
Wang [61]	IF-RC-ID	cmu	135	98	9	7.90	—	37.60
Furtado et al. [45]	Inf_02	cbhh	420	230	15	0.53	—	7.14
	Inf_03	cbhh	420	230	15	0.53	—	1.86
Calvi & Bolognini [51]	10	cbhh	420	275	13.5	1.10	1.11	2.92
	2	cbhh	420	275	13.5	1.10	1.11	0.52
	6	cbhh	420	275	13.5	1.10	1.11	0.78
Angel et al. [49]	1	rcb	243.8	162.6	4.8	11.51	—	8.19
	2b	rcb	243.8	162.6	4.8	10.86	—	4.00
	3b	rcb	243.8	162.6	4.8	10.14	—	6.00
Hak et al. [52]	TA1	cbvh	422	295	35	4.64	1.08	13.54
	TA2	cbvh	422	295	35	4.64	1.08	8.25
	TA3	cbvh	422	295	35	4.64	1.08	13.17
Da Porto et al. [62]	URM-D	cbvh	415	265	30	6.00	1.19	22.73
	URM-U	cbvh	415	265	30	6.00	1.19	18.46
Angel et al. [49]	6b	rcb	243.8	162.6	9.8	4.59	—	12.40

Note: cbvh: clay bricks with vertical holes; cbhh: clay bricks with horizontal holes; cmu: concrete masonry units; rcb: reclaimed Chicago common clay bricks.

The specimens vary in scale, including full-scale [45,49,51,52,55,62], two-third-scale [53,54,56,58,59], and one-half-scale [57,60,61] specimens. All represent single-story, single-bay RC frames with single-wythe infill walls. Approximately 80% of the infills used hollow clay bricks (with horizontal or vertical holes), while the remainder were concrete blocks (10%) or solid clay units (10%) (see Table 4). For hollow units, the compressive strength differs by orientation; infills typically exhibit higher capacities when compression acts parallel to the holes.

The IP loading was cyclic in most studies (monotonic only in [60,61]), while the OOP loading was monotonic (cyclic only in [52]). Given the limited dataset, variations in the loading protocols or application methods (airbags, four-point loading; Table 3) are not explicitly considered. It is noted, however, that Domenico et al. [58] found that four-point loading yields about 75% of the OOP capacity compared with distributed airbag loading, using a virtual work analysis of potential failure mechanisms.

Tables 3 and 4 report all the parameters required by Equations (1)–(10), including the experimental peak OOP strength, q_{exp} (in kPa). The measured peak OOP drifts at the infill mid-height are included in Table 3, although they were not utilized in the analytical predictions. For the infills with hollow units, the compressive strengths in both the vertical and horizontal directions, f_{vv} , and f_{vh} , are given when provided by the researchers. If the elastic modulus of concrete, E_c , was not reported, it was estimated using Eurocode 2, Part 1-1 [63] (Equation (11)):

$$E_c = 22 \times [(f_{ck} + 8)/10]^{0.3} \quad (11)$$

where E_c is the secant modulus of the elasticity of concrete (in GPa), and f_{ck} (in MPa) is the characteristic compressive cylinder strength.

4. Analytical Predictions of Out-of-Plane Strength of Infills

To assess the accuracy of the design models, experimental results are compared with analytical predictions. The consistency between predicted and measured values is evaluated using the following statistical indices: the correlation coefficient and the mean and standard deviation of the predicted-to-experimental ratios of the OOP capacity. The magnitude of scatter between predicted, $pred_i$, and experimental, exp_i , values is assessed by the average absolute error (AAE) determined by Equation (12) and the integral absolute error ratio (IAE) determined by Equation (13) (e.g., [64–66]). These indices, among others, quantify both the accuracy and scatter of predictions relative to experimental results:

$$AAE = \frac{\sum_{i=1}^N \left| \frac{pred_i - exp_i}{exp_i} \right|}{N} \times 100 \quad (12)$$

$$IAE = \frac{\sum_{i=1}^N |pred_i - exp_i|}{\sum_{i=1}^N exp_i} \times 100 \quad (13)$$

4.1. Infills Without Prior IP Loading

Table 5 summarizes the experimental OOP strengths, q_{exp} , of infills tested without prior IP damage, along with predictions from the Dawe and Seah [28] and Ricci et al. [29] models, q_{pred} . For hollow units, the compressive strength parallel to the arching direction is used (typically vertical, since $h_w/l_w \leq 1$ in all specimens). For specimens tested only in IP–OOP loading without a reference OOP test (e.g., [52,62]; specimen 6b in [49]), predicted OOP values are included for later use in Section 4.2.2. All infills were fully bounded to the RC frame (no gaps).

Table 5. Experimental and predicted values of the OOP strengths of infills without IP damage.

Experimental Study	Specimen Name	h_w/t_w	h_w/l_w	q_{exp} (kPa)	q_{pred} (kPa)		q_{pred}/q_{exp}	
					Dawe and Seah Equation (1)	Ricci et al. Equation (6)	Dawe and Seah Equation (1)	Ricci et al. Equation (6)
Milijaš et al. [55]	T1	8.4	0.91	25.16	30.5	25.3	1.21	1.01
Di Domenico et al. [53]	120S-OOP	15.3	1	9.94	8.4	12.2	0.84	1.23
De Risi et al. [56]	OOP	22.9	1	8.80	5.9	7.9	0.67	0.90
Akhoundi et al. [57]	SIF-O-1L-B	20.5	0.68	10.05	2.4	8.6	0.24	0.85
Ricci et al. [54]	120_OOP_4E	15.3	0.78	9.74	7.2	13.3	0.74	1.37
Di Domenico et al. [58]	OOP_4E	22.9	0.78	5.12	3.3	7.2	0.65	1.41
Sepasdar [60]	IF-ND	10.9	0.73	66.30	53.7	98.6	0.81	1.49
Furtado et al. [45]	Inf_02	15.3	0.55	7.14	2.4	6.5	0.34	0.91
Calvi & Bolognini [51]	10	20.4	0.65	2.92	2.0	4.2	0.68	1.43
Angel et al. [49]	1	34.1	0.67	8.19	6.6	8.6	0.81	1.05
Hak et al. [52]	— ^a	8.4	0.70	—	38.0	25.6	—	—
Da Porto et al. [62]	— ^a	8.8	0.64	—	39.0	30.1	—	—
Angel et al. [49]	— ^a	16.5	0.67	—	14.2	19.8	—	—
				Mean			0.70	1.17
				Standard Deviation			0.26	0.24
				Correlation	0.97	0.99		
				AAE (%)	34.33	23.20		
				IAE (%)	27.10	29.40		

^a Infills subjected to IP–OOP loading without any reference specimen loaded only OOP.

Figure 3 compares the experimental and predicted OOP strengths for four specimens, with comparable characteristics and from the same group of researchers. An increase in the slenderness ratio (h_w/t_w) from 15.3 to 22.9 is observed to more affect the infills with aspect ratios (h_w/l_w) of 0.78, as compared to infills with $h_w/l_w = 1$. This issue is better reflected by the Dawe and Seah [28] model, while the predictions of Ricci et al. [29] overestimate the q_{exp} . Figure 4 compares the predictions of the two models for three slender infills with aspect ratios around 0.65. The Dawe and Seah [28] model underestimates the q_{exp} , especially in the case of infill SIF-O-1L-B (Akhoundi et al. [57]), while the Ricci et al. [29] model predicts the infill OOP strength well.

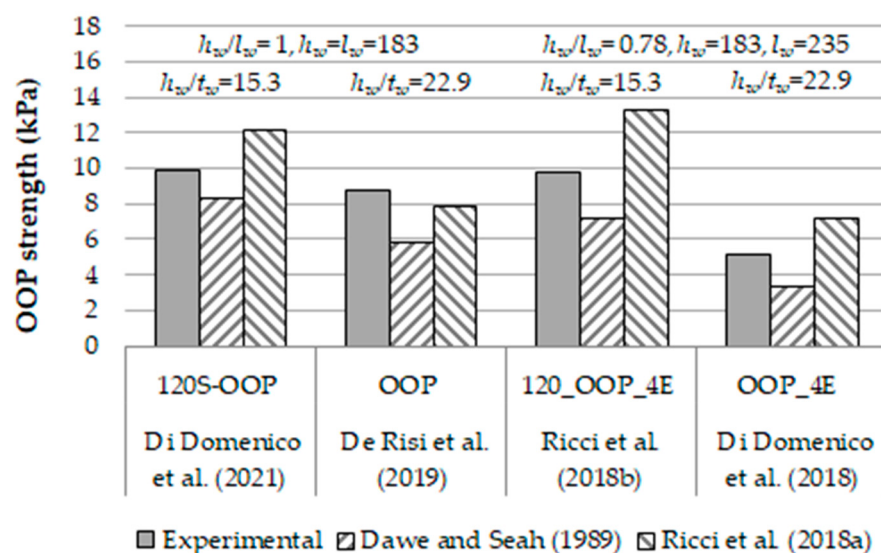


Figure 3. Experimental and predicted OOP strengths for four infills with aspect ratios (h_w/l_w) of 1 and 0.78 and slenderness ratios (h_w/t_w) of 15.3 and 22.9 (dimensions in cm). Di Domenico et al. (2021) [53]; De Risi et al. (2019) [56]; Ricci et al. (2018b) [54]; Di Domenico et al. (2018) [58].

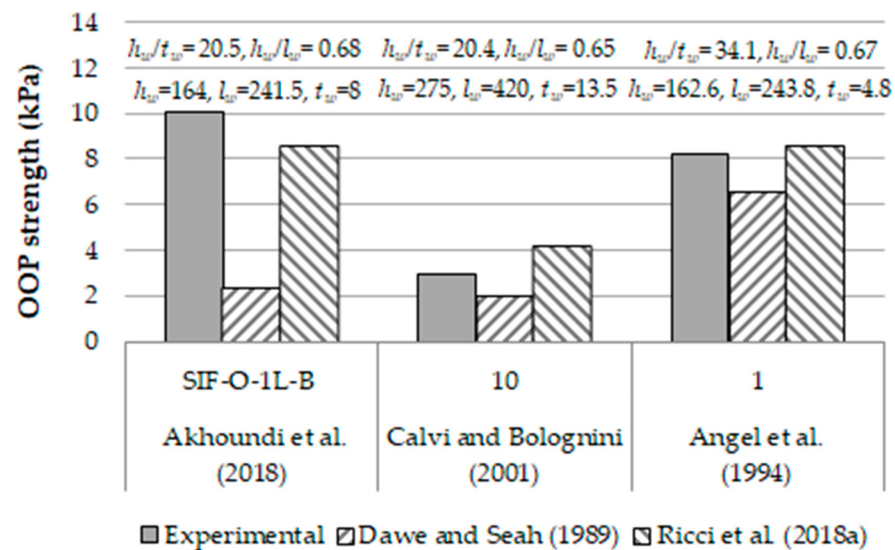


Figure 4. Experimental and predicted OOP strengths for three infills with aspect ratios (h_w/l_w) of 0.65, slenderness ratios (h_w/t_w) of 20.5, 20.4, and 34.1, and compressive strengths (f_{cw}) (MPa) of 1.17 [57], 1.10 [51], and 11.51 [49] (dimensions in cm). Akhoundi et al. (2018) [57]; Calvi and Bolognini (2001) [51]; Angel et al. (1994) [49].

The Dawe and Seah model is conservative because it was calibrated on infills in pinned steel frames and not on those in stiffer RC frames. For infills with $f_w < 1.17$ and/or $l_w/h_w > 20.5$, the model underestimates the general experimental capacity by more than 30% and up to 75% [45,51,57,58]. In the case of specimen SIF-O-1L-B [57], displayed in Figure 4, the underestimation of the OOP strength by 75% may be attributed to the weak frame members of the specimen combined with the high l_w and, hence, the low values of α , β (Equations (3) and (4)).

The Ricci et al. [29] model does not include the contribution of the length, l_w , of the infill, and hence, it cannot consider the effect of different l_w in otherwise identical infills, e.g., between specimens 120S-OOP and 120_OOP_4E, and between OOP and OOP_4E (Figure 3). The model overestimates more than 30% the OOP strength of certain infills (e.g., OOP_4E ($h_w/t_w = 22.9$), ID-ND (with concrete blocks)); however, no specific conclusions may be drawn.

4.2. Strength Reduction Due to Prior IP Loading

The reduction in the OOP strength of infills because of prior IP loading is represented by the factor R , designated as the ratio of the IP–OOP strength of an infill previously subjected to IP loading at a specific value of in-plane drift (IDR) divided by the OOP strength of an identical infill without any prior IP loading.

4.2.1. R-Factor Evaluation

Figure 5 plots experimental R -values, $q_{exp(IP-OOP)}/q_{exp(OOP)}$, against the maximum imposed IP drift (IDR). Two groups of behavior are identified: the infills tested by Angel et al. [49], Ricci et al. [59], Furtado et al. [45], and Calvi and Bolognini [51], designated as “group A”, display an increased reduction in the OOP strength at similar values of imposed IP drift, as compared to the remaining infills of the database, which are henceforth designated as “group B”.

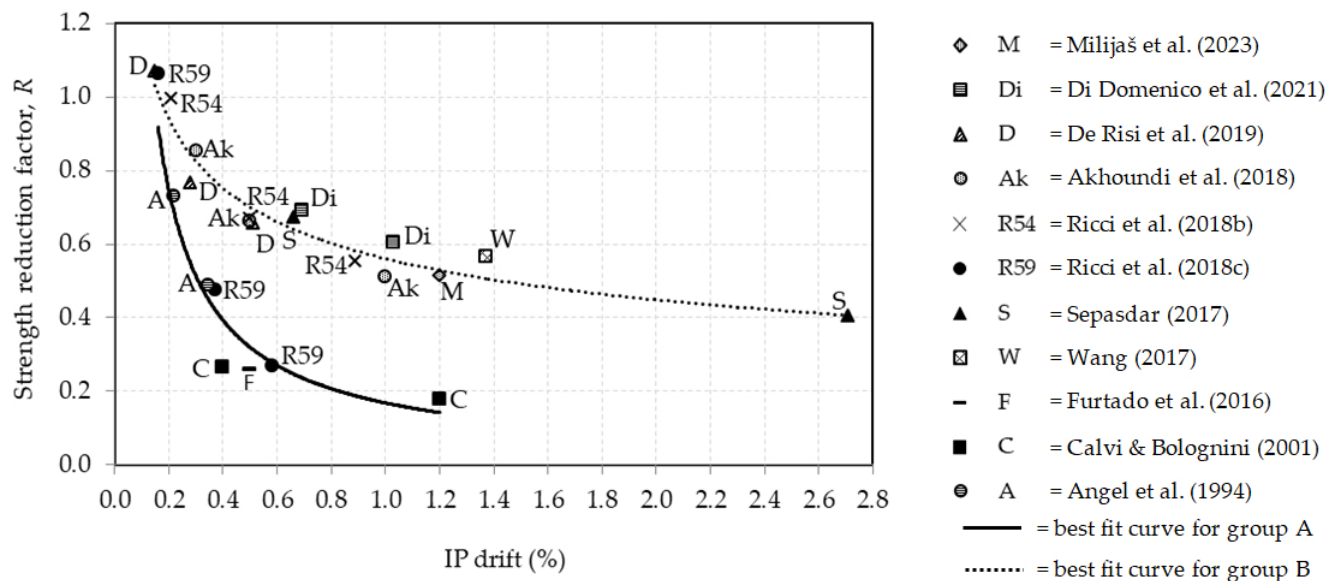


Figure 5. Experimental OOP strength reduction factor, R , versus maximum IP drift (IDR) for previously IP-loaded infills from different experimental studies. Milijaš et al. (2023) [55]; Di Domenico et al. (2021) [53]; De Risi et al. (2019) [56]; Akhouni et al. (2018) [57]; Ricci et al. (2018b) [54]; Ricci et al. (2018c) [59]; Sepasdar (2017) [60]; Wang (2017) [61]; Furtado et al. (2016) [45]; Calvi & Bolognini (2001) [51]; Angel et al. (1994) [49].

Infills of group A apparently possess increased vulnerability compared to the infills of group B. More particularly the infills of Angel et al. [49] and Ricci et al. [59] have high slenderness ratios, i.e., $h_w/t_w = 34.1$ and 22.9 , respectively, while the infills of Furtado et al. [45] have particularly low compressive strength: $f_w = 0.53$ MPa. The infills tested by Calvi and Bolognini [51] have $h_w/t_w = 20.4$ and $f_w = 1.1$ MPa. The specimens of De Risi et al. [56] with $h_w/t_w = 22.9$, $h_w/l_w = 1$, and $f_w = 2.37$ MPa belong to group B, with mild OOP strength reduction, which may be attributed both to the higher infill compressive strength and the aspect ratio (h_w/l_w) of 1, which resulted in better OOP behavior (see also Section 4.1).

The increased strength degradation for comparatively weaker infills has been observed in experimental studies (e.g., [26]) but has not yet been reflected in the existing models. Based on regression of experimental data, Equation (14) is proposed, which includes two different expressions, depending on the values of the geometrical and strength infill properties. The proposed R -factor for vulnerable infills, i.e., $h_w/t_w > 20.5$, is practically the same as Equation (10) [43], as both equations were derived from the same specimens.

$$R = \begin{cases} 0.167 \times IDR^{-0.936}, & \text{for } (h_w/t_w > 20.5 \text{ and } h_w/l_w < 1) \text{ or } f_w \leq 1.10 \text{ MPa} \\ 0.557 \times IDR^{-0.31}, & \text{for } h_w/t_w \leq 20.5 \text{ or } (h_w/t_w > 20.5 \text{ and } h_w/l_w = 1) \end{cases} \quad (14)$$

Table 6 compares the experimental and predicted R -values from the existing models [43,53,54] with those from the proposed R_{mod} . The new factor provides the best fit across the dataset, with AAE and IAE values below 10%.

Figure 6 compares the experimental R_{exp} with the analytically predicted R -factors for the specimens in the database. It may be observed that for the thicker infills of Milijaš et al. [55] ($h_w/t_w = 8.4$) and Sepasdar [60] ($h_w/t_w = 10.9$, specimen IF-D1), which were subjected to IP drifts equal to or less than 1.20%, the available Equations (7)–(9) for R overestimate the IP–OOP strength; i.e., they underestimate the strength reduction because of prior IP damage.

Table 6. Reduction factors (R): experimental and analytically predicted.

Experimental Study	Specimen Name	IDR (%)	R_{exp}	R_{pred}			
				Di Domenico et al. Equation (7)	Ricci et al. Equation (8)	Ricci et al. Equation (9)	Proposed R_{mod} Equation (14)
Milijaš et al. [55]	T2	1.20	0.51 ^a	0.77	0.81	0.54	0.53
Di Domenico et al. [53]	120S-IPM-OOP	0.69	0.69	0.73	0.53	0.53	0.62
	120S-IPH-OOP	1.03	0.60	0.55	0.40	0.36	0.55
De Risi et al. [56]	IPL-OOP	0.15	1.07	1.00	0.88	1.00	1.00
	IPM-OOP	0.28	0.76	0.76	0.57	0.56	0.83
	IPH-OOP	0.51	0.65	0.49	0.38	0.32	0.69
Akhoundi et al. [57]	SIF-IO (0.3)	0.30	0.85	0.51	0.63	0.53	0.81
	SIF-IO (0.5)	0.50	0.66	0.35	0.44	0.32	0.69
	SIF-IO (1.0)	1.00	0.51	0.21	0.27	0.16	0.56
Ricci et al. [54]	120_IP + OOP_L	0.21	0.99	1.00	1.00	1.00	0.90
	120_IP + OOP_M	0.50	0.67	0.84	0.66	0.72	0.69
	120_IP + OOP_H	0.89	0.55	0.55	0.45	0.41	0.58
Ricci et al. [59]	IP + OOP_L	0.16	1.06	0.94	0.84	0.97	0.93
	IP + OOP_M	0.37	0.48	0.51	0.47	0.43	0.42
	IP + OOP_H	0.58	0.27	0.37	0.34	0.28	0.28
Sepasdar [60]	IF-D1	0.66	0.67	0.95	0.86	0.81	0.63
Wang [61]	IF-D2	2.71	0.40	0.34	0.33	0.21	0.41
	IF-RC-ID	1.37	0.57	0.56	0.52	0.40	0.51
Furtado et al. [45]	Inf_03	0.50	0.26	0.66	0.66	0.72	0.32
Calvi & Bolognini [51]	2	1.20	0.18	0.18	0.24	0.14	0.14
	6	0.40	0.27	0.39	0.52	0.40	0.39
Angel et al. [49]	2b	0.34	0.49	0.45	0.29	0.46	0.45
	3b	0.22	0.73	0.62	0.39	0.72	0.69
Correlation				0.72	0.63	0.72	0.97
AAE (%)				26.42	35.05	31.40	9.86
IAE (%)				21.60	28.80	25.80	8.30

^a Example for specimen T2, $R_{exp} = 12.89 \text{ kPa} / 25.16 \text{ kPa} = 0.51$ (see Table 4 for q_{exp}).

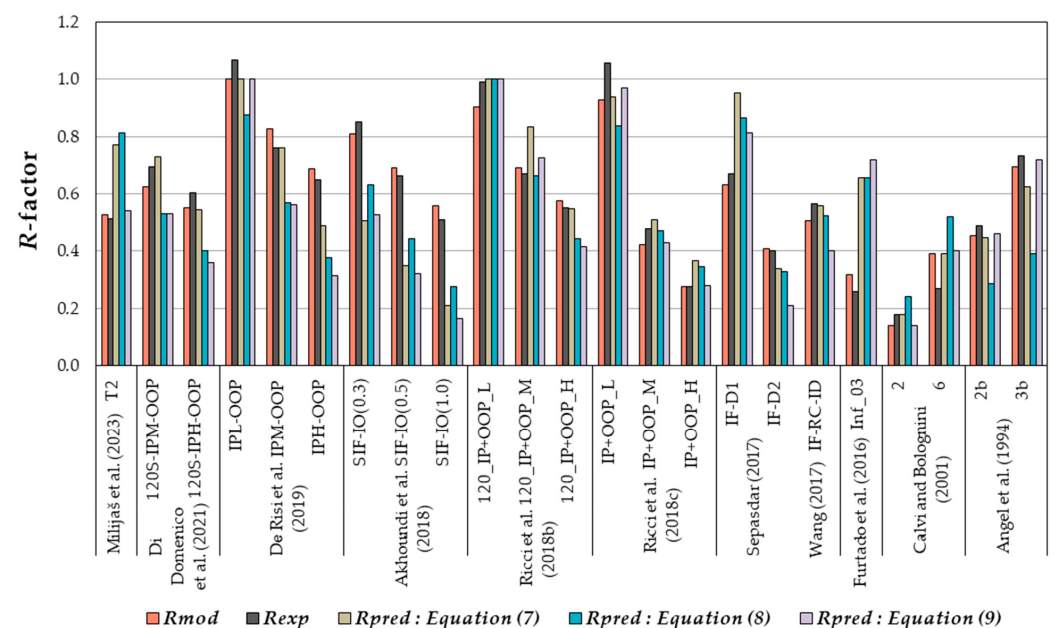


Figure 6. Experimental, R_{exp} , and predicted, R_{pred} , R -factors of 23 infill specimens from different studies. Milijaš et al. (2023) [55]; Di Domenico et al. (2021) [53]; De Risi et al. (2019) [56]; Akhoundi et al. (2018) [57]; Ricci et al. (2018b) [54]; Ricci et al. (2018c) [59]; Sepasdar (2017) [60]; Wang (2017) [61]; Furtado et al. (2016) [45]; Calvi & Bolognini (2001) [51]; Angel et al. (1994) [49].

4.2.2. Prediction of IP–OOP Strength

The IP–OOP strength of infills is calculated as follows:

$$q_{u,IP-OOP} = q_{pred} \times R_{mod} \quad (15)$$

where q_{pred} is obtained from Dawe and Seah [28] or Ricci et al. [29] (Table 5), and R_{mod} is the proposed reduction factor.

Table 7 presents comparisons for all specimens, including those without reference OOP tests. The results show that the prediction accuracy depends primarily on the q_{pred} , while the R_{mod} effectively captures the degradation due to IP drift.

Table 7. Experimental and predicted IP–OOP strengths of masonry infills with previous IP damage.

Experimental Study	Specimen Name	q_{exp} (kPa)	$q_{u, IP-OOP} = q_{pred} \times R_{mod}$ (kPa)		$(q_{pred} \times R_{mod})/q_{exp}$	
			Dawe and Seah Equation (1)	Ricci et al. Equation (6)	Dawe and Seah Equation (1)	Ricci et al. Equation (6)
Milijaš et al. [55]	T2	12.89	16.0	13.3	1.24	1.03
Di Domenico et al. [53]	120S-IPM-OOP	6.90	5.2	7.6	0.76	1.11
	120S-IPH-OOP	6.00	4.6	6.8	0.77	1.13
De Risi et al. [56]	IPL-OOP	9.39	5.9	8.0	0.63	0.85
	IPM-OOP	6.72	4.8	6.6	0.72	0.98
	IPH-OOP	5.74	4.0	5.5	0.70	0.95
Akhoundi et al. [57]	SIF-IO(0.3)	8.58	1.9	6.9	0.22	0.81
	SIF-IO(0.5)	6.67	1.6	5.9	0.25	0.89
	SIF-IO(1.0)	5.13	1.3	4.8	0.26	0.93
Ricci et al. [54]	120_IP + OOP_L	9.67	6.5	12.1	0.67	1.25
	120_IP + OOP_M	6.49	5.0	9.2	0.76	1.42
	120_IP + OOP_H	5.37	4.1	7.7	0.77	1.43
Ricci et al. [59]	IP + OOP_L	5.44	3.1	6.7	0.57	1.23
	IP + OOP_M	2.44	1.4	3.1	0.58	1.25
	IP + OOP_H	1.37	0.9	2.0	0.68	1.46
Sepasdar [60]	IF-D1	44.40	34.0	62.5	0.77	1.41
	IF-D2	26.40	22.0	40.3	0.83	1.53
Wang [61]	IF-RC-ID	37.60	27.1	49.8	0.72	1.32
Furtado et al. [45]	Inf_03	1.86	0.8	2.1	0.42	1.11
Calvi & Bolognini [51]	2	0.52	0.3	0.6	0.54	1.13
	6	0.78	0.8	1.6	1.00	2.11
Angel et al. [49]	2b	4.00	3.0	3.9	0.75	0.97
	3b	6.00	4.6	6.0	0.76	1.00
Hak et al. [52]	TA1	13.54	18.6	12.6	1.38	0.93
	TA2	8.25	15.9	10.7	1.93	1.30
	TA3	13.17	21.1	14.2	1.61	1.08
Da Porto et al. [62]	URM-D	22.73	26.9	20.8	1.19	0.91
	URM-U	18.46	20.5	15.8	1.11	0.86
Angel et al. [49]	6b	12.40	12.2	16.9	0.98	1.37
		Mean			0.81	1.16
		Standard Deviation			0.38	0.27
		Correlation	0.91	0.98		
		AAE (%)	35.69	22.74		
		IAE (%)	30.70	24.50		

Figure 7 demonstrates the comparison between the experimental and predicted IP–OOP strengths for the infills of two studies with an aspect ratio (h_w/l_w) of 0.7. The Ricci et al. [29] model predicted the test results well, while the Dawe and Seah [28] model considerably underestimated the infill strength of Akhoundi et al. [57] (Figure 7a) and overestimated the infill strength in the case of Hak et al. [52] (Figure 7b).

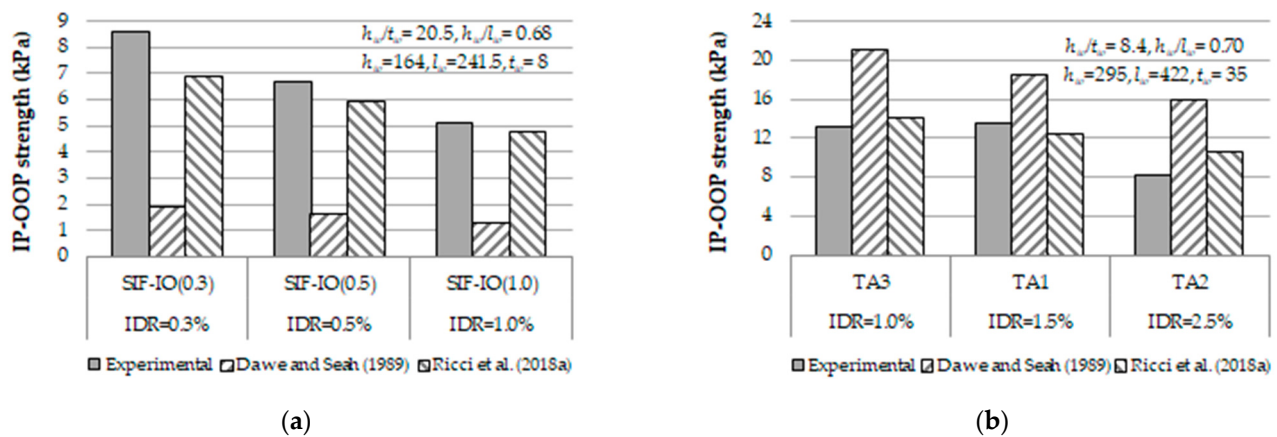


Figure 7. Experimental and predicted IP–OOP strengths of infills subjected to three levels of IP drift for slender and thick infills with an aspect ratio (h_w/l_w) of 0.7 (dimensions in cm). (a) Akhoundi et al. [57]; (b) Hak et al. [52].

4.3. Infills with Gaps

The type of connection between infills and the surrounding RC elements has proved to significantly affect the performance of RC-infilled frames, e.g., [67,68]. Research studies have focused on the impact of better attaching masonry infill walls to the RC frame to improve the seismic response of the infilled frame, e.g., [69–71]. The presence of gaps between infills and RC frames has a critical impact on the OOP strength. Table 8 summarizes tests on gapped specimens, compared with their fully connected counterparts. Predictions were made using the Dawe and Seah [28] model, which explicitly accounts for gaps.

Table 8. Experimental and predicted OOP strengths of infills with gaps between infills and RC frame members.

Experimental Study	Specimen Name	Top Gap (mm)	Side Gaps (mm)	h_w/t_w	h_w/l_w	f_{wv} (kPa)	Dawe and Seah		
							q_{exp} (kPa)	q_u (kPa)	q_u/q_{exp}
Di Domenico et al. [58]	OOP_4E	—	—	22.9	0.78	1.80	5.12	3.3	0.65
	OOP_3E	2	—	22.9	0.78	2.21 ^c	4.09	1.5	0.36
Di Domenico et al. [44]	80_OOP_3Eb	40	—	22.9	0.78	2.88 ^c	4.28	1.8	0.42
Di Domenico et al. [58]	OOP_2E	—	NR ^b	22.9	0.78	1.81	3.39	2.1	0.61
Ricci et al. [54]	120_OOP_4E	—	—	15.3	0.78	1.65	9.74	7.2	0.74
Di Domenico et al. [44]	120_OOP_3E	40	—	15.3	0.78	2.12 ^c	7.81	3.3	0.42
	120_OOP_2E	—	30	15.3	0.78	2.21	5.58	5.6	1.00
Akhoundi et al. [57]	SIF-O-1L-B	—	—	20.5	0.68	1.17	10.05	2.4	0.24
	SIF-O-1L-A	0 ^a	—	20.5	0.68	1.17 ^d	8.81	0.6	0.06
Sepasdar [60]	IF-ND	—	—	10.9	0.73	9.40	66.3	53.7	0.81
Wang [61]	IF-RC-TG (3E)	10	—	10.9	0.73	9.00 ^d	18.5	18.8	1.02
	IF-RC-SG (2E)	—	5	10.9	0.73	9.00	36.5	34.0	0.93

^a Failure of interface between infill and top RC beam; ^b infill mortared to RC frame only along upper and lower sides; ^c f_{wh} is used for the calculation of the OOP strength; ^d f_{wh} is not provided; hence, f_{wv} is used for the calculation of the OOP strength.

In the case of a gap between the infill and RC top beam or a gap between the infill and RC columns, arching only along the horizontal or vertical direction, respectively, is assumed. The apposite compressive strength of the infill, i.e., along the horizontal or vertical direction, f_{wh} or f_{wv} , respectively, is used [47]:

- For clay brick infills ($h_w/t_w = 15$ – 23), a top gap (2 to 40 mm) reduced the q_{exp} by 16–20%, while side gaps produced even larger reductions.

- For concrete masonry infills ($h_w/t_w \approx 11$), a 10 mm top gap reduced the q_{exp} by up to 72% [60,61], which is more severe than that for side gaps.

It is observed that the Dawe and Seah model generally predicts a lower capacity for top gaps compared to side gaps, which does not always match experimental trends.

Figure 8 illustrates the impact of the presence of the two configurations of gaps on the experimental and analytical OOP strengths of infills for three groups of specimens.

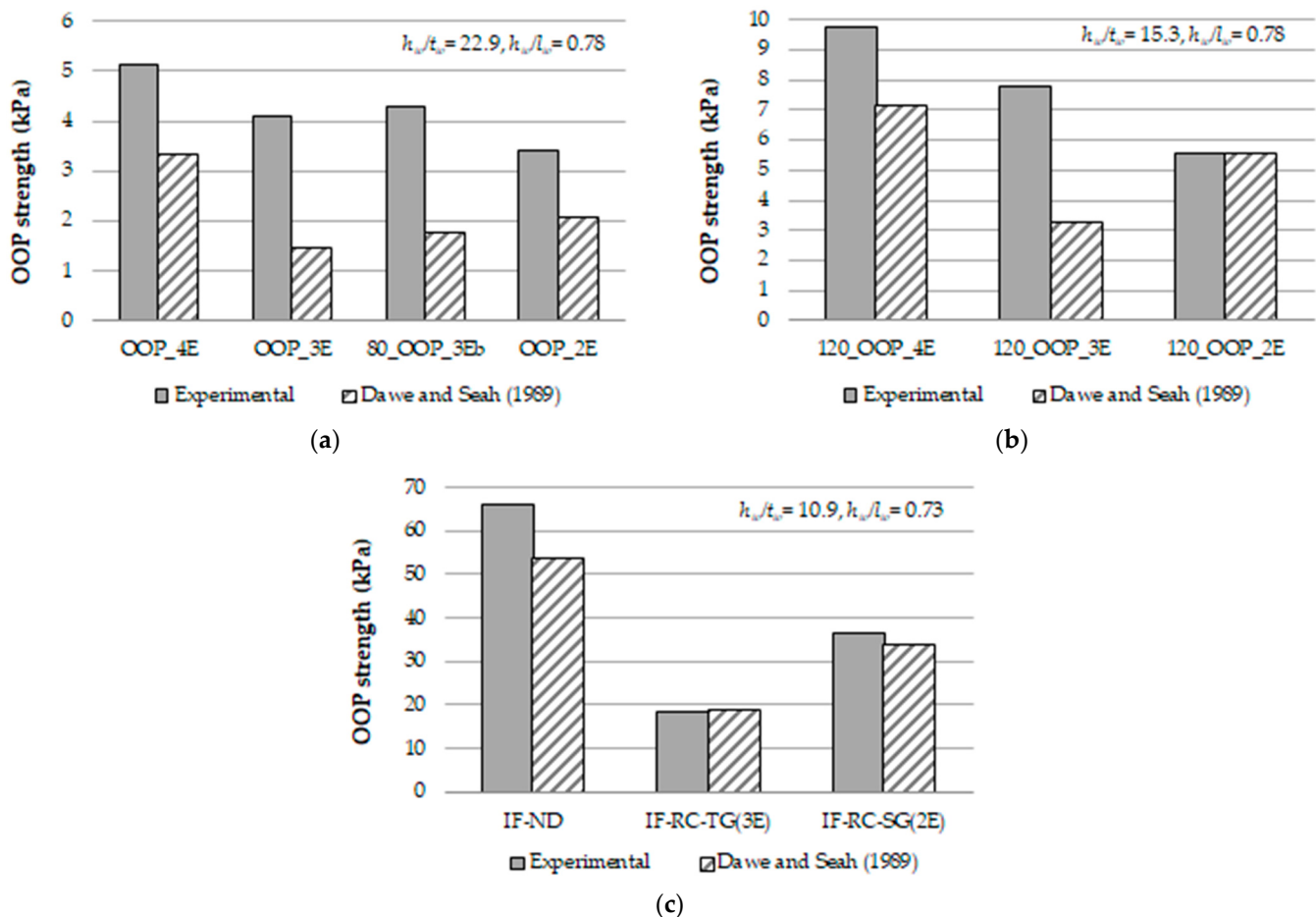


Figure 8. Experimental and predicted OOP strengths of infills for different types of connections between the infill and RC frame (4E: fully connected infill; 3E: gap between RC beam and top of infill; 2E: gap between infill and RC columns) (dimensions in cm). (a) Di Domenico et al. [44,58]; (b) Ricci et al. [54]; Di Domenico et al. [44]; (c) Sepasdar [60]; Wang [61].

Shake-table tests indicate that the OOP behavior under dynamic conditions may differ significantly. For example, Dazio et al. [19] observed the rocking behavior of gapped infills without immediate failure, while well-restrained panels failed more abruptly. Tu et al. [16] noted that OOP failure becomes imminent once separation from the frame occurs due to inertial forces caused by their self-weight.

5. Conclusions

This paper investigated the out-of-plane (OOP) capacity of unreinforced masonry (URM) infills enclosed in RC frames, with particular emphasis on the influence of prior in-plane (IP) loading and the presence of gaps. A comprehensive database of experimental results was assembled, and available analytical models were evaluated. It is noted that the vast majority of infills in the database are made of hollow clay units and, hence, the

findings principally address infills of hollow clay bricks. Based on this study, the following conclusions are drawn:

1. The models of Dawe and Seah [28] and Ricci et al. [29], broadly recognized for their good predictions, fail to accurately describe the effect of the individual infill properties on the OOP strength of infills without prior IP damage. The model of Ricci et al. results in better overall predictions but omits the infill length and is occasionally un-conservative, without apparent reason. The Dawe and Seah model appears to be over-conservative in the presence of vulnerability factors, namely, a high slenderness ratio and low infill strength. A more comprehensive model for the OOP strength is deemed necessary, possibly including two equations, i.e., for infill with/without increased vulnerability OOP, similar to the proposed R -factor.
2. The proposed R -factor (ratio of IP–OOP/OOP strength of infills), accounts for vulnerability characteristics of the OOP behavior of infills, i.e., a high slenderness ratio and low infill strength, within ranges defined from experimental results. The new design equations resulted in the improved IP–OOP strength prediction of the infills in the database, in comparison to other existing models.
3. The analytical IP–OOP strength should be calculated as a product of the R -factor with the OOP strength, q_u , of an infill without prior IP loading, both obtained from design models. For accurate predictions, design formulas of both the R -factor and q_u should be reliable over a broad database without exclusion of any specimens, rather than matching different R -factors with different q_u values in search of good statistical indices for the product $R \times q_u$.
4. Gapped infills are significantly weaker than fully bounded infills, particularly in the presence of a gap between the top and the RC frame. Reductions in the experimental capacity ranged from 16% to over 70%, depending on the unit type, slenderness, and gap location. The Dawe and Seah model resulted in conservative predictions. It appears that the type of units significantly affects the OOP behavior of gapped infills. More experimental work is required to further explore this issue.
5. In order to further study the important issue of the OOP behavior of infills, further experimental studies are required, which should also focus on other types of infills, e.g., double-leaf infills and infills with concrete-block units. Furthermore, dynamic tests, especially full-scale tests, are required to more reliably reproduce the actual behavior of infills in major earthquakes.

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Abbreviations

The following abbreviations are used in this manuscript:

RC	Reinforced concrete
OOP	Out-of-plane
IP	In-plane
IP–OOP	In-plane and subsequent out-of-plane loading
IDR	In-plane drift

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