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EFFECT OF MASONRY INFILLS ON DUCTILITY ENHANCEMENT OF REINFORCED CONCRETE FRAMES

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ABSTRACT: It is widely recognised that the masonry infills are designed as non-structural components in reinforced concrete frames in most of the present version seismic codes. However, the great frame-infill interaction has substantially changed the load transfer path and modes of failure to the original capacity of RC bare frames. Therefore, it is necessary to fully understand the inherent characteristics of masonry walls and its interaction mechanism with the RC frame. This paper presents a statistical analysis with a total of 13 groups of experimental data obtaining from different researchers around the world. The specimens are scaled varying from 1/3 to 1/2 and are all subjected to quasi-static lateral loading. The displacement ductility and corresponding interstorey drift demand have been thoroughly analysed. It is shown that the displacement ductility of infilled frames is commonly larger than that of bare frames. The corresponding plastic deformation ratio further shows the effect of infills on the enhancement of deformation capacity of infilled frames. Moreover, it is argued that the 2.5% interstorey drift demand specifying the ultimate limit state in most of the current seismic codes has been underestimated the interaction effect of masonry infills and overestimated the structural deformation capacity. Therefore, a more rational value of 2.0% drift capacity is recommended for infilled RC frame structural systems.

1. Introduction

The masonry-infilled reinforced concrete frames have been regarded as one of the most commonly-used structural systems for buildings in the world. In general, the bounding frames are designed to seismic codes under the capacity design procedures, while the masonry infills are treated as non-structural elements to full contact with the frame. However, it seems that this type of design philosophy does not perform well in practice under field investigations from past catastrophic earthquakes. The primary failure of structures come from the vulnerability of masonry infills and the unexpected shear failure concentrating at critical regions of columns or beam-column joints.

Many useful studies have been done to analyse the seismic behaviour of infilled RC frames. The comparison between the gravity load-designed and seismic load-designed of reinforced concrete frames, the different types of materials of masonry infills, the significant influence of infills on the contribution of lateral stiffness and strength, and the opening effect of infill panels, have all been discussed in the literature (Mehrabi et al., 1996; Mosalam et al., 1997; Murty and Jain, 2000; Kakaletsis and Karayannis, 2007).

Although the studies of infilled RC frames have been conducted over the years, it is indeed surprising that there still far be consensus on whether the effect of infills is positive to the overall structure system. On the basis of limited knowledge, it can be regarded that the masonry infills have normally play a contradictory role in the reinforced concrete frame buildings. On one hand, the masonry infills are normally treated as a first line of lateral defence owing to the great interaction with surrounding frame. The enhancement of stiffness and strength is apparent and can be an advantage to the overall structure. On the other hand, the strong interaction could dramatically affect the original capacity design provision of frame and lead to shear failure concentrating at critical regions. The infills may be prematurely failed because of the inherent brittle nature as well.

The primary objective of the study is to figure out a fundamental issue of infill walls: what is the dominant role for masonry infills and whether it can be performed as a positive contributor to the overall structure. The studies are on the basis of statistical analysis from a total of 13 groups of experimental data tested in the past years. The displacement ductility and corresponding plastic deformation ratios have been thoroughly compared between bare frame and infilled frames. All data are oriented on the favourable effect of masonry infills. It is evident that a considerable higher ductility can be achieved when considering the infill walls. The interstorey drift demand specifying the ultimate limit state have been also discussed, and a more rational value of 2.0% drift ratio is recommended for the infilled frame structure system.

2. Statistical Data

2.1. Basic Properties of Test Data

There are totally 13 groups of experimental data obtained from different researchers around the world. All of the specimens are tested under the in-plane quasi-static loads and a majority of them are conducted within the past five years. The basic properties of different specimens are summarised in Table 1. Most of specimens are single-storey and single-bay with the scale varying from 1/3 to 1/2.

Table 1 – Basic properties of test specimens

Researcher	Specimen ID	Scale of specimen	Number of stories, bays	Clear bay×height	Aspect ratio (L/h)	Column section	Beam section
Al-Chaar et al. (2002)	No.1	1/2	1,1	2032×1426	1.42	203×127	127×197
	No.2						
	No.3						
Aly et al. (2001)	FRAME1	1/2	1,1	2030×1540	1.32	200×120	120×200
	FRAME2						
Baran & Sevil (2010)	SP1	1/3	2,1	1400×825	1.70	100×150	150×150
	SP2						
Colangelo (2005)	V10	1/2	1,1	2500×1425	1.75	200×200	200×250
	V11						
Kakaletsis (2011)	B	1/3	1,1	1350×900	1.50	150×150	100×200
	S						
Kuang & Wang (2014)	CB	1/2	1,1	2400×1450	1.66	250×250	200×300
	CC						
Mehrabi et al.(1996)	#1	1/2	1,1	2311×1538	1.50	203×203	152×229
	#4						
	#5						
	#6						
	#7						

Misir et al. (2012)	BaF	1/2	1,1	2250×1375	1.64	250×150	150×250
	SBF						
	LBF						
Puglisi et al. (2009)	0-bar	1/2	1,1	1600×1600	1.00	160×130	130×160
	2-bar						
Essa et al. (2014)	F1	1/2	1,1	1850×1500	1.23	200×120	120×200
	F3						
Yuksel et al. (2010)	Bare frame	1/3	1,1	1133×900	1.26	200×100	200×200
	Infilled wall						
Zhou et al. (2014)	BF	1/3	1,1	2000×1100	1.82	160×160	100×200
	CIWF						
Stylianidis (2012)	CB	1/3	1,1	1590×960	1.50	150×150	100×200
	F1						

2.2. Mechanical Properties of Test Data

The Table 2 and Table 3 have listed a total of 13 bare frame tests and 18 infilled frame tests. The drift ratio of yielding state, peak load state, and ultimate state are presented. Moreover, the displacement ductility is highlighted to reflect the deformation capacity of specimens.

Table 2 – Mechanical properties of bare frame specimens

Researcher	**Specimen ID**	**Yielding state**		**Ultimate state**		**Ductility**	**Peak load state**		
		Δ_y **(yield) /mm**	**Drift (Δ_y)**	Δ_u **(ultimate) /mm**	**Drift (Δ_u)**		**Peak load /kN**	Δ_p **(Peak load) /mm**	**Drift (Δ_p)**
Al-Chaar et al. (2002)	No.1	9.54	0.67%	113.25	7.94%	11.87	34.3	50.34	3.53%
Aly et al. (2001)	FRAME1	34.35	2.23%	62.30	4.05%	1.81	55.95	49.95	3.24%
Baran & Sevil (2010)	SP1	5.28	0.64%	20.63	2.50%	3.88	13.78	8.29	1.00%
Colangelo (2005)	V10	32.80	2.30%	110.89	7.78%	3.38	58.02	69.37	4.87%
Kakaletsis (2011)	B	7.42	0.82%	25.16	2.80%	3.39	44.80	10.81	1.20%
Kuang & Wang (2014)	CB	17.60	1.21%	49.94	3.44%	2.84	221.41	33.93	2.34%
Mehrabi et al.(1996)	#1	--	--	--	--	--	--	--	--
Misir et al. (2012)	BaF	19.78	1.44%	51.02	3.71%	2.58	100.92	34.31	2.50%
Puglisi et al. (2009)	0-bar	29.20	1.83%	83.55	5.22%	2.86	39.90	64.79	4.05%
Essa et al. (2014)	F1	12.94	0.86%	86.66	5.78%	6.69	66.28	72.00	4.80%
Yuksel et al. (2010)	Bare frame	3.33	0.37%	46.23	5.14%	13.88	65.95	26.92	2.99%

Zhou et al. (2014)	BF	11.71	1.06%	35.20	3.20%	3.01	88.02	18.19	1.65%
Stylianidis (2012)	BF	5.05	0.53%	35.85	3.73%	7.10	21.25	11.94	1.24%

Table 3 – Mechanical properties of infilled frame specimens

Researcher	Specimen ID	Yielding state		Ultimate state		Ductility	Peak load state		
		Δ_y (yield) /mm	Drift (Δ_y)	Δ_u (ultimate) /mm	Drift (Δ_u)		Peak load /kN	Δ_p (Peak load) /mm	Drift (Δ_p)
Al-Chaar et al. (2002)	No.2	2.18	0.15%	136.87	9.60%	62.78	84.1	39.46	2.77%
	No.3	2.17	0.15%	133.15	9.34%	61.36	89	10.47	0.73%
Aly et al. (2001)	FRAME2	13.35	0.87%	40.36	2.62%	3.02	150.04	27.95	1.82%
Baran & Sevil (2010)	SP2	1.90	0.23%	15.68	1.90%	8.43	49.99	8.55	1.04%
Colangelo (2005)	V11	25.85	1.81%	98.61	6.92%	3.81	64.98	49.57	3.48%
Kakaletsis (2011)	S	4.32	0.48%	20.94	2.33%	4.84	80.30	8.13	0.90%
Kuang & Wang (2014)	CC	15.54	1.07%	54.74	3.78%	3.52	415.61	31.63	2.18%
Mehrabi et al.(1996)	#4	2.96	0.19%	19.04	1.24%	6.43	151.68	8.08	0.53%
	#5	4.06	0.26%	21.06	1.37%	5.18	266.27	8.70	0.57%
	#6	3.59	0.23%	29.34	1.91%	8.18	214.56	9.43	0.61%
	#7	3.48	0.23%	11.64	0.76%	3.34	444.97	8.17	0.53%
Misir et al. (2012)	SBF	4.98	0.36%	31.32	2.28%	6.28	137.62	20.44	1.49%
	LBF	7.88	0.57%	50.09	3.64%	6.36	97.09	40.64	2.96%
Puglisi et al. (2009)	2-bar	5.29	0.33%	87.89	5.49%	16.63	97.63	29.54	1.85%
Essa et al. (2014)	F3	10.24	0.68%	38.38	2.56%	3.75	105.25	24.56	1.64%
Yuksel et al. (2010)	Infilled wall	3.66	0.41%	14.92	1.66%	4.08	121.92	7.64	0.85%
Zhou et al. (2014)	CIWF	3.85	0.35%	15.28	1.39%	3.97	296.05	8.35	0.76%
Stylianidis (2012)	F1	2.03	0.21%	20.47	2.13%	10.06	43.75	12.01	1.25%

3. Comparison and Discussion

The statistical analysis are all on the basis of backbone curves from different tests, which are normally presented by the lateral resisting loads plotted against the corresponding displacement. As demonstrated in Fig. 1, it can be seen that the displacement ductility μ can be conventionally calculated as a ratio of ultimate displacement Δ_u over against yielding displacement Δ_y. The value of Δ_y and Δ_u can be traced back to the idealised elastic-perfectly plastic model, which the backbone curve has been intersected by a straight line representing the 80% or 85% of maximum strength F_{max} through the point of separately on the ascending and degrading part.

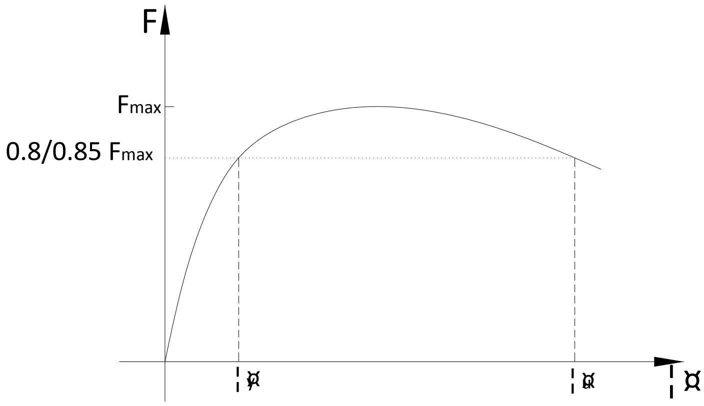


Fig. 1 – Concept of Ductility μ

3.1. Displacement Ductility μ

The displacement ductility has been recognised as the most significant index for structure to reflect its deformation capacity. As illustrated in Fig. 2, the ductility of bare frame and infilled frame are all highlighted. It is obviously seen that a considerable higher ductility of infilled frames than that of bare frames. Specifically, the average value of ductility for infilled frame can be reached to almost 5.1, whereas the value can be only about 2.97 for bare ones.

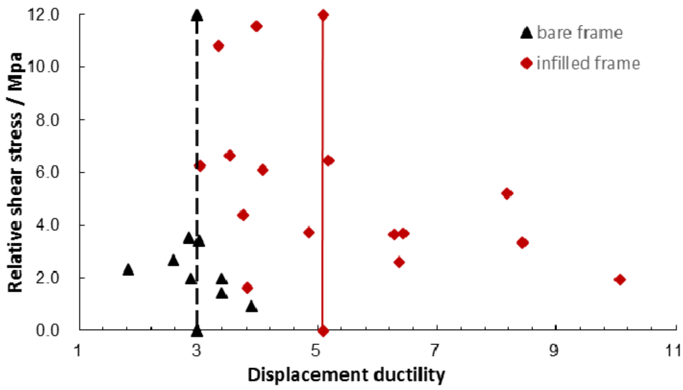


Fig. 2 – Data of Ductility Data for Bare Frame and Infilled Frame

3.2. Plastic Deformation Ratio for Structures (Δ_p / Δ_u)

In the deformation of structures, the plastic deformation Δ_p can be functionally defined as the ultimate displacement Δ_u deduct the yielding displacement Δ_y. Then, the value of Δ_p / Δ_u can be deemed as the plastic deformation ratio for structures under the reversed-cyclic loads. As illustrated in Fig. 3, it is indicated that the value of plastic deformation ratio for infilled frame is obviously larger than the bare frame ones, which the average value of infilled frame can be achieved to over 80%, while the value is only about 70% for bare frames. This is implied that the structure can be suffered to a much larger plastic deformation when the infill wall is involved.

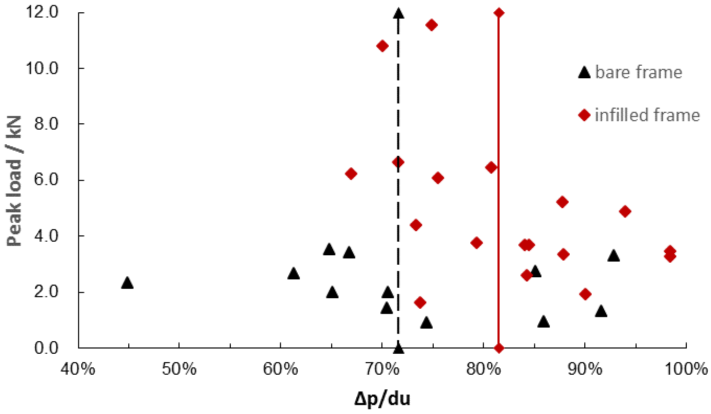


Fig. 3 – Percentage of Plastic Deformation over Maximum Deformation

3.3. Absolute Value of $\Delta_{p\text{-infill}}$ and $\Delta_{p\text{-bare}}$

Under the above discussions, it can be concluded that the deformation capacity of structures has been enhanced after considering the involvement of infills. However, this is not means that the absolute value of plastic deformation Δ_p in infill frames is always larger than that of bare frames. In fact, according to statistical data, it is found that the ratio of $\Delta_{p\text{-infill}}$ / $\Delta_{p\text{-bare}}$ is strongly associated with the initial design option. As demonstrated in Figure 4, it is clearly seen that the average value of $\Delta_{p\text{-infill}}$ can be almost 1.2 times larger than that of the $\Delta_{p\text{-bare}}$ when seismic design is proceeded, while the value can be only 0.7 for the non-seismic design data. This is rational because the failure of bounding frame owing to the infill interaction has been mitigated under the seismic design level.

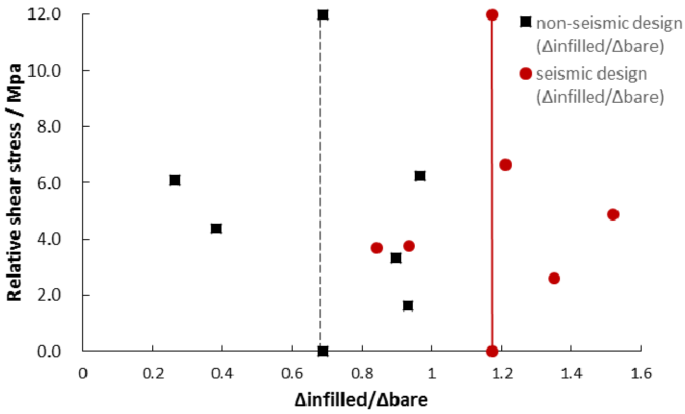


Fig. 4 – Comparison of Plastic Deformation

3.4. Interstorey Drifts under Different Failure States

Deflection control can be considered an effective way to assess the seismic performance of structures. The drift ratios regarding the yielding state, peak load state, and ultimate state of statistical data have all been obtained, and the results are shown in Fig. 5. Generally, the 2.5% allowable interstorey drift demand reflecting the ultimate limit state has been specified in most of the seismic codes, while Eurocode 8 only mandated the serviceability limit state with the value of 0.5% when considering the brittle nature of infills.

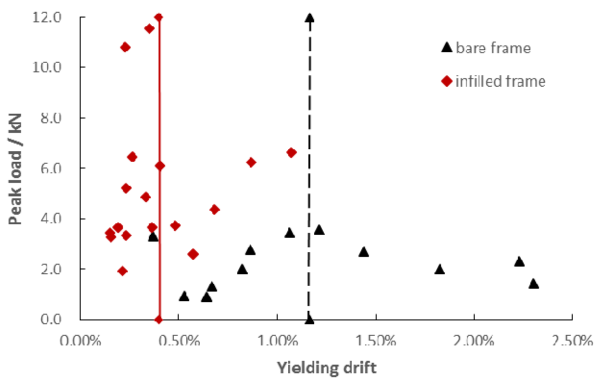
Table 4 – The codes requirements of interstorey drifts

Codes of practice	Serviceability limit state	Ultimate limit state
ASCE 7	--	2.5%
Eurocode 8	0.5%	--
GB 50011-2010	0.18% (1/550)	2% (1/50)
NZS 1170.5	--	2.5%
UBC 1997	--	2.5%

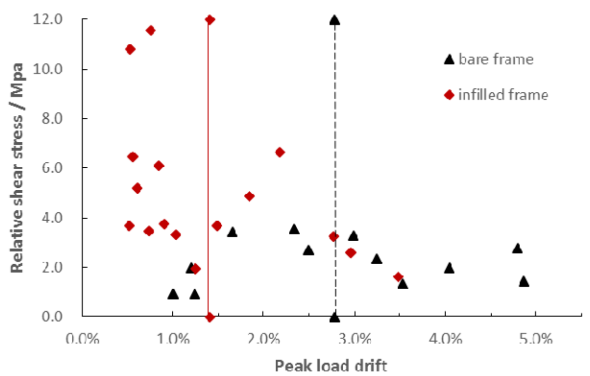
Although it is clearly noticed the dramatic different of drift ratios between bare frames and infilled ones, it is indeed argued that the 2.5% interstorey drift demand specifying the ultimate limit state of structures has been seriously underestimated the interaction effect of masonry infills and overestimated the structural deformation capacity. In fact, the measured average interstorey drift for infilled frames at the ultimate state can be only of 2.11%, which is much lower than the design value. From this point of view, only the Chinese seismic code GB 50011-2010 agrees well with the test data and gives a conservative limit value 2.0%

Table 4 –Loading state vs interstorey drift

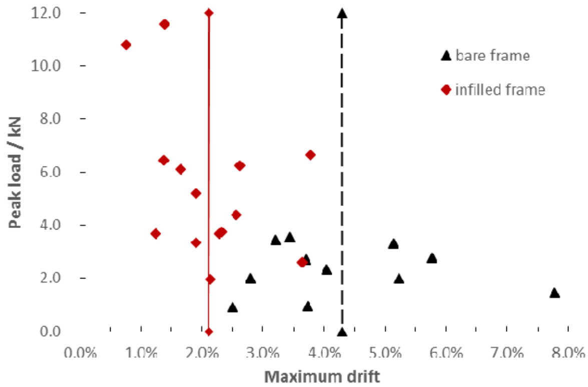
Statistical data	Yielding state	Peak load state	Ultimate limit state
Bare frame	1.16%	2.78%	4.30%
Infilled frame	0.40%	1.41%	2.11%



(a) Yielding drift



(b) Peak load drift



(c) Maximum drift

Fig. 5 – Interstorey Drifts at Different Failure States

4. Conclusions

The statistical analysis is conducted to systematically assess the effect of masonry infills on the overall deformation capacity of infilled RC frames. There are total 13 groups of experimental data varying from different researchers around the world. Most of specimens are single-storey and single-bay with a scale factor from 1/3 to ½, and all specimens were tested under quasi-static loads.

Based on the analysis results, it is concluded that masonry infills have the favourable effect on the global seismic behaviour of an infilled frame system. In general, masonry infills can greatly improve the strength and stiffness of structures. However, there is still a much controversy on whether the infills have a positive contribution to ductility behaviour as well as deformation capacity of structures. The statistical analysis has proved that the displacement ductility factor of 5.1 can be achieved for infilled frames, whereas it is 2.97 for bare frames in average, which is much lower than the expectation. In addition, it is shown from the studies that the plastic deformation ratio of an infilled frame is generally higher than that of a bare frame.

On the other hand, the rational interstroey drift ratio of infilled frames at the ultimate limit state has been recommended. The statistic data indicated that the measured average drift ratio for infilled frames at the ultimate limit state is 2.11%, which is much lower than the value of 2.5% given in most present seismic codes. Hence the seismic codes generally overestimate the overall structural deformation capacity of RC moment-resisting frames, even considering the contribution of infills. Based on this statistical analysis, it is recommended that a rational interstroey drift ratio be 2.0% for the design of infilled RC frames.

5. Acknowledgements

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