Research Note

Modification Factor of Masonry Infills, Required in Seismic Rehabilitation; A Preliminary Study Based on Experimental Results

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ABSTRACT

An extensive investigation is conducted on experimental data to improve modification factors of masonry infills. For this, available experimental data are classified based on the frame and infill materials. Then a sensitivity analysis is carried out for the effective parameters on the m-factor, including relative stiffness of infill to the frame, the material of infill or frame, aspect ratio, etc. To calculate m-factors of specimens, both the backbone and the envelope curves of the hysteresis curves, proposed in ASCE41-06 and ASCE41-13, respectively, are applied. The obtained results confirm ASCE41-13 for giving more conservative m-factor values. Sensitivity analysis shows that infill m-factors highly depend on the infill and frame materials, rather than the infill aspect ratio and relative stiffness of the frame to the infill. Finally, some values are proposed for m-factors of infill panels, made of clay brick or clay tile, surrounded by steel or concrete frames.

Keywords:
Modification factor; Seismic rehabilitation; Infill panel; Masonry

1. Introduction

Infills are normally used in buildings for architectural reasons. They raise the stiffness and strength of the building substantially and change seismic behavior of structures. Therefore, overlooking infills is not always on the safe side and may lead to local collapse in beams and columns of the surrounding frames or in their connections.

Research on infills started six decades ago [1] and is still the subject of many current research studies. Lack of sufficient ductility is the main deficiency of masonry infills. Consequently, some infills that have more ductility have been recently proposed; Kahn and Hansen [2] showed that multi-ply infills are more ductile than single layer infills; Aref et al. [3] applied Polymer matrix composite infill panels, made of two-layer fiber polymer and a core made of vinyl; Mohammadi et al. [4] has applied a sliding fuse at the mid-height of the wall to achieve ductile infill with adjustable stiffness and strength.

Infills in urban buildings of more than 15 years old are normally made of regular masonry materials. They have been ignored in the analysis and designing phases for the complication of modeling and having many uncertainties [1]. However, they are considered as structural elements in rehabilitation projects.

Based on rehabilitation guidelines, all component actions can be classified as either deformation-controlled or force-controlled. Classification as a deformation controlled components have been defined in rehabilitation guidelines by designation of m-factor or nonlinear deformation capacities. The component demand modification factor to account for expected ductility is defined as m-factor [5-6]. Rehabilitation guidelines such as ASCE-41-13 [5], ASCE-41-06 [6], FEMA-356 [7], etc. have proposed some values for modification factors (m) for infills in different performance levels. According to ASCE-41, the m-factor of an infill panel can be calculated through the idealized load-displacement diagram of a specimen, obtained by cyclic testing, in either the first or the third quadrants of the curve. The guidelines have proposed some values for the m-factor of regular infill panels, depending on infill aspect ratio and ratio of the frame shear strength to the infill expected strength [5-6].

The aim of all researches mentioned above is to enhance the seismic behavior and ductility of a special infill panel. In addition, a quantitative measure of the ductility of infills is ambiguous in all past researches. It means that, a special value cannot be assigned to an infill with specific materials. Therefore, those researches cannot be applicable in the common procedures of vulnerability of structures proposed in rehabilitation guidelines such as ASCE-41-13[5], ASCE-41-06 [6], FEMA-356 [7], etc. Besides, based on experimental results, the hysteresis behavior of infill panels has illustrated unsymmetrical behavior in both the first and the third quadrants. However, ASCE41-06 has proposed some values for "m" that are very close to m-factors of very ductile elements such as beams of special moment resisting frames and the same in both quadrants.

Consequently, there is a need to investigate the value of m-factors and the procedures to calculate them for infilled frames with various types of materials and frames. This will contribute to effective decisions on rehabilitating techniques for infill panels. In this paper, modification factors of infill panels are calculated and compared with the values proposed in the rehabilitation guidelines, based on experimental researches of the literature. Moreover, the proposed procedures of ASCE41-06 [6] and ASCE41-13 [5] to obtain the idealized load- displacement curve are compared.

2. What Is the Modification Factor?

Based on guidelines, ASCE-41 [5-6] and FEMA-356 [7], the estimated expected amount of member deformation is compared with tolerable extents of nonlinear action for specific performance levels. In the procedure of rehabilitation and vulnerability of structures, one global R factor cannot be used to represent all features of a system. Elastic demand should be reduced differently for elements with variable deformation capacities.

For primary deformation-controlled elements, such as infill panels, unreduced elastic member forces are compared with component capacities that are increased by the m-factor according to ASCE41 [5-6] formula, as follows:

$$Q_g + Q_E \leq m \kappa Q_{CE} \quad (1)$$

where Q_g and Q_E are the unreduced linear-elastic gravity and seismic forces, respectively. κ is a knowledge-based factor depending on the type of condition assessment used, and Q_{CE} is the expected force capacity of a component [5-7].

For infill panels, some cracking is permitted for immediate occupancy. Therefore, this feature provides a masonry wall that is capable of reserving strength after cracking. Loss of wall lateral strength is considered as the life safety structural performance level, in which the potential of the infill panels is high to drop out of the frames. For the collapse prevention performance level, there is not any m-factor for the infill panels in the rehabilitation guidelines. Consequently, it is assumed that the surrounding frame should remain stable following the loss of an infill panel [5-6].

3. How to Calculate the m-Factor?

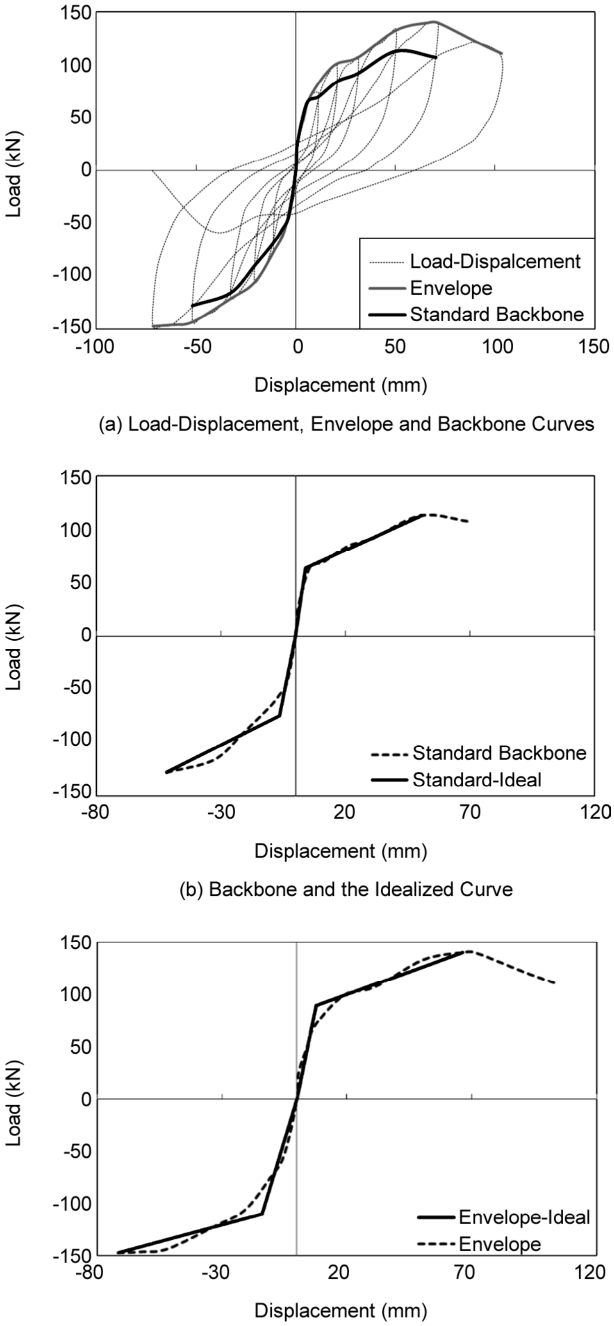
Based on ASCE41, the m-factor is obtained through the idealized force-deformation curves of infill specimens in the first and third quadrants [5] and it is assumed that the obtained m-factor is conservative. How to obtain the idealized force-deformation curve is different in ASCE41-06 and ASCE41-13. Based on ASCE41-06, it is drawn through the intersection of the first cycle curve for the i^{th} deformation step with the second cycle curve of $(i\text{-}1)^{th}$ deformation step for all i steps. However, based on ASCE41-13, the curve is a smooth curve drawn through each point of peak displacement during the first cycle of each increment of loading. The idealized force-deformation curves, proposed in ASCE41-06 and ASCE41-13 are called "backbone curve" and "envelope", respectively, hereafter in this paper [5-6].

In this paper, m-factors of infill panels are calculated based on previous experimental studies through both the backbone curves and envelopes of their hysteresis curves. The m-factors of the specimens are calculated for both the first and the third quadrants of the hysteresis curves, in the same way of ASCE 41. This paper has focused on m-factors for the life safety performance level, shown as 'm_{LS}', except mentioned otherwise.

For instance, the backbone and envelope curves for a 10 cm thick masonry specimen called MM are shown in Figure (1); the specimen was a 10 cm thick clay brick infill surrounded by a steel frame. Load displacement, envelop and backbone curves of the specimen MM are shown in Figure (1a). These curves are idealized to bilinear curves as shown in Figure (1b) and (1c), respectively [8].

An idealized curve is shown in Figure (2). The m-factor can be calculated for life safety performance as [6]:

$$m_{LS} = 0.75 \times \frac{0.75 \times D_v}{D_y} \tag{2}$$



(a) Load-Displacement, Envelope and Backbone Curves

(b) Backbone and the Idealized Curve

(c) Envelope and the Idealized Curve

Figure 1. Load-displacement, backbone, envelope and idealized curves of MM [8].

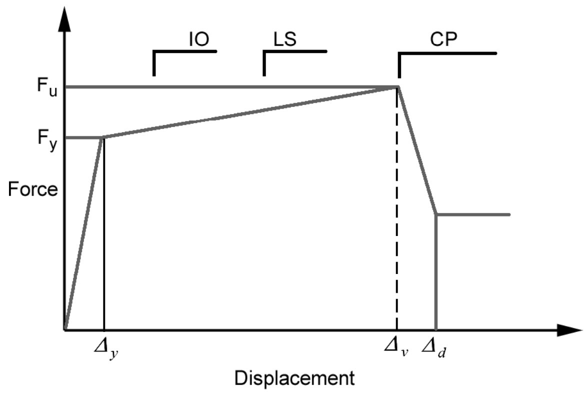


Figure 2. General behavior of structural elements [5].

The first and third quadrants of the idealized standard curve give m-factors of 7.14 and 4.46, respectively. These values are changed to 4.78 and 2.9 for the envelope curve. The obtained values show that the calculated m-factors from the first and the third quadrants of load-displacement diagram are substantially different. In addition, m-factors calculated through envelope curves are not matched with the m-factors of the backbone curve. In other word, it seems that the modification factors obtained by envelop curve are lower than the ones of the backbone curve.

In this paper, the average of four obtained values of m-factors (for both backbone and envelope, in the first and the third quadrants of a load-disp. behavior) are considered as the m-factor of the infill panel. However, it would be better to consider the minimum m-factors of the standard and envelope curves as the modification factor of an infill, conservatively, because actual load-displacement behavior of an infill in a real earthquake is expected to locate between the envelope and backbone curves. It is because most strength deterioration in infill panels occurs up to the third cycles of loading, which are considered in the backbone curve.

4. Sensitivity Analysis on the m-Factors of Infilled Frames

4.1. Comparing m-Factor of Infilled Frames with the Bare Frames

In this section, m-factors of bare and infilled frame specimens are compared. As shown in Table (1), a single conclusion cannot be drawn on the influence of infill on the m-factor; the presence of infills sometimes increases and sometimes decreases m-factor of the frames. In the research specimens of Kakaletsis and Karayanni [9] the average m-factors of the infilled specimens, *S* and *IS*, are respectively lower and higher than that of the bare frame (B-specimen), both for the envelope and backbone curves. For specimens of Parsa and Sarvghadmoghadam [10], and also the specimens of Puglisi et al. [11], the presence of infill raised m-factors of the frames. Although the m-factor of Misir et al.[12] specimen calculated by the idealized backbone curve is increased by the presence of infill, this parameter computed by the idealized envelop curve is decreased. Regarding Kaltakci et al. [13] specimens, the m-factor of the frame is raised by the presence of infill for long infilled frame specimens ($h/l = 2$) whereas it is decreased for high specimens ($h/l = 0.5$).

4.2. Infill Type

ASCE-41 has a single Table for m-factors of all infilled frames with different materials. However, the obtained results of this part show that the m-factor highly depends on the infill or frame material. The m-factors are calculated for the first and the third quadrants, of both the backbone and envelope curves of the specimens. As shown in Table (1), the modification factors of infills surrounded by concrete frames depend on the infill material. The same is true for infills in steel frames, shown in Table (2). In continuous parts, this assumption will be explained comprehensively. Regarding infill material, as shown in Table (2), for the specimens of reference Gavrilovic and Sendova [14], the average m-factor of Eltozol infill specimen (with m = 4.3) is greater than masonry (with m = 3.4), and this, itself, is greater

Table 1. Calculated m-factor of infill specimens in concrete frames.

Reference	Infill Type	Specimen	h/l	Standard Method			Envelope Based Method			Average of the Averages
				1st Quadrant	3rd Quadrant	Average	1st Quadrant	3rd Quadrant	Average	
Parsa [10]	Bare Frame	Figure (4)	0.81	1.2	1.5	1.4	1.1	1.5	1.3	1.35
	Clay Brick	Figure (5)		2.1	1.9	2	2.3	2.2	2.3	2.15
	Perforated Brick	Figure (6)		2.2	1.8	2	2.4	1.8	2.1	2.05
Sevil [17]	Clay Brick	REFB	0.58	6.5	3.8	5.1	5.8	5.9	5.8	5.45
Altin [18]	Clay Tile	Spec. 1	0.58	4.1	2.5	3.3	4.1	2.1	3.1	3.2
Puglisi [11]	Bare Frame	Figure (8a)	1	2.4	2.4	2.4	2.2	2.5	2.4	2.4
	Clay Tile	Figure (8c)		4.1	3.2	3.7	4	3.4	3.7	3.7
Calvi [19]	Clay Brick	Non reinforced	0.65	Not available			3.7	2.1	2.9	-
		ϕ 6mm					4.5	1.7	3.1	-
		ϕ 5mm					1.4	1.4	1.4	-
Yanez [20]	Clay Brick	Pattern 1	0.63	Not available			3.4	6.7	5	-
Kakaletsis [9]	Bare Frame	B	0.67	3.7	4.1	3.9	2.7	2	2.4	3.15
	Clay Brick	S		1.4	3.1	2.3	1.4	1.1	1.6	1.95
		IS		4.2	4.6	4.4	3.8	3.7	3.8	4.1
Misir [12]	Bare Frame	BaF	0.63	2.2	2.2	2.2	4.7	2.8	3.8	3
	Clay Brick	SBF		1.5	2.3	2	4.2	4	4.1	3.05
Mehrabi [21]	Concrete Block	Spec.4	0.67	6.6	3.3	5	5.5	2	3.7	4.35
		Spec.5		7.2	5.9	6.6	4.1	-		
		Spec.6		4.7	2.3	3.5	1.7	3.1	2.4	2.95
		Spec.7		5.7	3.0	4.3	5.3	3	2	3.15
	Concrete Block	Spec.11	0.48	3.5	2.9	3.2	3.6	2.5	3.1	3.35
		Spec.12		4.6	2.9	3.8	3.8	2.6	3.2	3.5

Table 2. Calculated m-factor of infill specimens in steel frames.

Reference	Infill Type	Specimen	h/l	Standard Method			Envelope Based Method		
				1st Quadrant	3rd Quadrant	Average	1st Quadrant	3rd Quadrant	Average
Mohammadi [8]	Clay Brick	MM	0.7	7.1	4.5	5.8	4.8	2.9	3.8
Tasnimi [22]	Clay Brick	SW	0.8	2.0	4.8	3.4	1.6	3.5	2.6
Flanagan [23]	Clay tile	17-pull	0.82	6.9	3.5	5.2	6.2	3.3	4.7
Eldakhakhni [24]	Concrete block	SP-2	0.81	4	2.5	3.5	4.4	2.7	3.6
Imran [16]	Clay brick	Model 2	1	2.2	2.5	2.3	2.9	2.2	2.5
	AAC	Model 1		2	1.9	1.9	5.7	3.6	4.7
Gavrilovic [14]	Bare	M1	0.75	2.7	2.5	2.6	2.9	1.6	2.2
	Masonry	M2		2.8	3.8	3.3	2.6	4.5	3.5
	Syporex	M3		2.5	2.5	2.5	3.8	3.1	3.5
	Gypsum	M4		1.3	4.4	2.8	1.4	6.3	3.9
	Eltozol	M5		5.6	2	3.8	8.2	1.5	4.9
Markulak [15]	AAC	OY-2	0.75	2.3	4.5	3.4	4.1	2.3	3.2
	Clay tile	OG-1		2	2.7	2.4	2	2.9	2.5
Kaltakci [13]	Bare frame	N110	2	Not available			1.4	2.8	2.1
		N110	1				1.5	1	1.3
		N110	0.5				1.7	2.5	2.1
	Brick infill	N111	2	Not available			2.7	1.7	2.2
		N111	1				1.3	1.2	1.3
		N111	0.5				1.0	1.1	1.1

than m-factors of gypsum (with m = 3.4) and Syporex (m = 3) infill specimens (Syporex is a block made of lightweight concrete, Eltozol is a frequent material in Skopje for walls). For the specimens of the reference Markulak et al. [15] and Imran and Aryanto [16], the m-factor of AAC (Autoclaved Aerated Concrete) is normally greater than that of clay tile infill. The average m-factor of all AAC infill specimens is 3.3 (average of 4 calculated values of the above-mentioned m-factors). This result surrounding the importance of infill types and frames on ductility and seismic behavior of infill panels has been implied in past researches [1-3].

4.3. Relative Stiffness of Infill to Frame (λ_l)

Based on ASCE-41, the m-factor of infill panels depends on two parameters: 1- Ratio of frame to infill expected lateral strengths (β), 2- infill aspect ratio (h_{inf} / l_{inf}) [5-6].

For most experimental specimens, calculating β is not possible, because of the lack of information about infills or frame material properties; however, relative stiffness of an infill to a frame, referred to as λ_l, can be estimated and used instead of β. λ_l is an important parameter for infills; based on previous studies [1], the equivalent width of an infill in macro modeling and its general behavior depend on this parameter, which is as follows [5-6]:

$$\lambda_l = \left[\frac{E_{eq} \times t_{\inf} \times \sin(2\theta)}{4E_{fe} \times I_{col} \times h_{\inf}} \right]^{1/4} \tag{3}$$

h_{inf} = height of infill panel (cm);

l_{inf} = length of infill panel (cm);

E_{fe} = expected modulus of elasticity of frame material (Pa);

E_{me} = expected modulus of elasticity of infill material (Pa);

I_{col} =moment of inertia of column, (cm^4);

t_{inf} = thickness of infill panel and equivalent strut (cm);

θ = angle whose tangent is the infill height to length aspect ratio (radians);

The relation between λ_l and m-factor for some specimens is shown in Table (3), which is plotted in a graph in Figure (3). As shown, the data is very scattered, showing that there is not a logical relationship between λ_l and the m-factor of the specimens. It is noticeable that more experimental results are required to have a better suggestion.

Table 3. Calculated m-factors of infill specimens in comparison with ASCE-41 proposed m-factors.

Reference No.	Specimen	Aspect Ratio (h/l)	λ_1	m-Factor		
				ASCE-41 [5-6]	Average of Standard Method	Average of Envelop Method
Mehrabi [21]	Spectrum 4	0.67	0.038	6.5	5.0	3.7
	Spectrum 5	0.67	0.038	6.5	6.6	-
	Spectrum 6	0.67	0.033	6.5	3.5	2.4
	Spectrum 7	0.67	0.032	6.5	4.5	4.2
	Spectrum 11	0.48	0.036	6	3.2	3.1
	Spectrum 12	0.48	0.036	6	3.8	3.2
Parsa [10]	Figure (5)	0.81	0.042	6.8	2.0	2.3
	Figure (6)	0.81	0.031	6.8	2.0	2.1
Mohammadi [8]	MM	0.70	0.023	6.6	5.8	3.8
Tasnimi [22]	SW	0.80	0.027	6.5	3.4	2.6
Sevil [17]	REFB	0.58	0.046	7.8	5.1	5.8
Altin [18]	Specimen 1	0.58	0.052	6.3	3.3	3.1

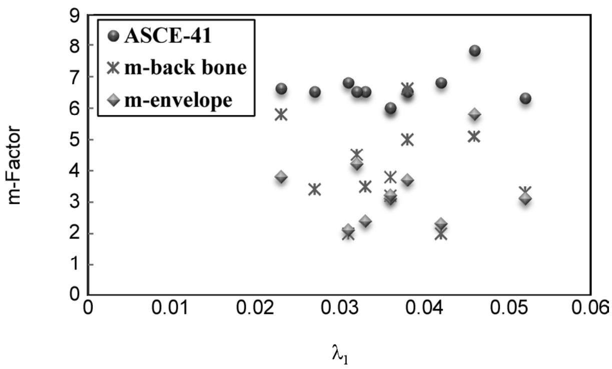


Figure 3. Relation between λ_l and the m-factor of the specimens in Table (3).

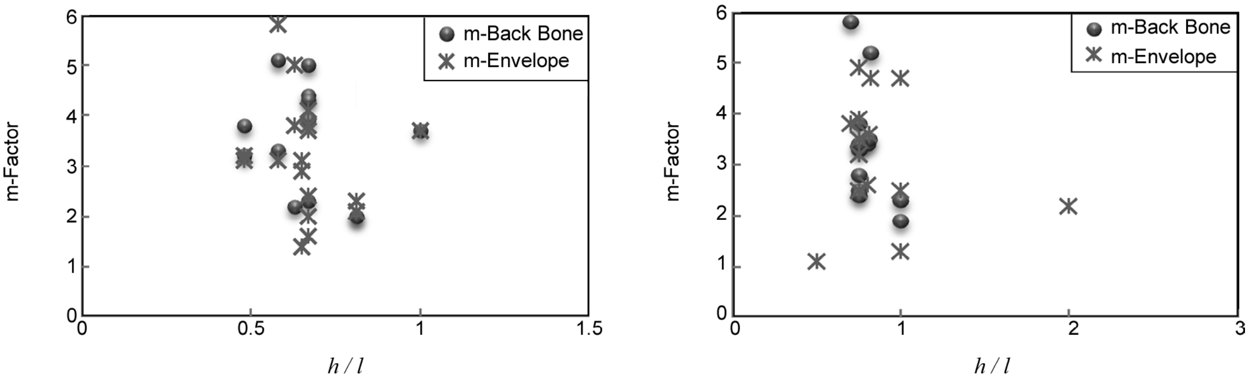
4.4. Aspect Ratio

Based on Table 7-8 of ASCE-41-06 (2007), infill panels are categorized into three groups with aspect ratios of 0.5, 1.0 and 2.0, respectively. The m-factors of infill with different aspect ratios are obtained by interpolating between the table values. Therefore, based on ASCE-41-06, the panels with greater aspect ratios are expected to have higher m-factors.

Aspect ratios of most specimens in Tables (1) and (2) are between 0.5 and 1.0. The relation of the m-factors with the infill aspect ratio for concrete frames and steel frames have been illustrated in Figure (4a) and Figure (4b), respectively. As shown, for the infills neither in concrete frame, nor in steel frame, a reasonable relationship is observed between the aspect ratio and the m-factor of the specimens. It is noticeable that more experimental results are required to have a better suggestion.

5. A Discussion on ASCE Proposed Values for m-Factor of Infilled Frames

Based on ASCE-41-06 [6], the m-factor should be calculated through the idealized force-deformation curves, both in the first and the third quadrants (positive force versus positive deformation, and negative force versus negative deformation, respectively). Therefore, for each specimen, two m-factors can be calculated for both of the backbone and the envelope curves. In this method, it is presumed that the first and third quadrants of the idealized curve give almost the same values for the m-factor. However, the results in Tables (1) and (2) show that this assumption is doubtful for the infill panels. Furthermore, based on ASCE-41-06 [6], the m-factor of an infilled frame depends only on the infill aspect ratio (h_{inf} / l_{inf}) and the ratio of frame to infill expected strengths (β) [6]. The m-factor is assumed



(a) Infills in Concrete frames (b) Infills in Steel frames

Figure 4. Relation of the m-factor with the infill aspect ratio.

independent of infill or frame materials, but the obtained results in Figures (3) and (4) show that it highly depends on the infill material, rather than other variables. Moreover, ASCE41-06 has proposed some values for "*m*" that are greater than the obtained values of this study, almost for all specimens, as it is observed in Table (3) [5-6]. These values are not conservative, especially considering some of them are very close to the m-factors of very ductile elements such as beams of special moment resisting frames. This shows that the values of infill m-factor proposed in ASCE-41 should be modified.

6. Suggesting Modification Factors for Regular Infills

The results of Tables (1) to (3) are summarized in Table (4). In this table, average and standard deviation of the calculated m-factors (both for the first and third quadrants of load-displacement curves) are shown. The specimens are categorized based on the frame or infill type. In this table, Ave. and Std. stands for the average and standard deviation, respectively. As shown in this table, the envelope curves give more conservative values for m-factors for all types of infills both in steel frame and concrete frame. Therefore, these results confirm applying envelope, instead of the backbone curve to calculate the m-factor as it is proposed in the new version of ASCE-41 [5]. The table also shows that for almost all cases, infills in concrete frames have greater m-factors than modification factors in steel frames.

All in all, based on the obtained results of Table (4), it is suggested to consider m-factors of clay brick and clay tile infills in steel frames as 3.2 and 2.3, respectively. For infills in concrete frames, both of these values can be assumed as 3.4.

The modification factors of AAC infills are higher than clay tile infills, based on Table (2); however, it is suggested to assume it conservatively the same as clay tile infills and equals to 2.3. It is noticeable that more experimental results are required to have a better suggestion.

The obtained results can be easily generalized to the modification factor corresponding to Immediate Occupancy (*IO*) level of performance, although this paper has been focused on the performance of Life Safety; based on the codes ASCE-41[5-6] the maximum drift of an element in *IO* is 0.67 of that in LS, thus: $m_{IO}=0.67\times m_{LS}$. Therefore, the m-factor of *IO* performance (m_{IO}) for clay brick and clay tile infilled steel frames should be considered as 2.1 and 1.5, respectively. These values are both raised

Table 4. Calculated m-factors of infill specimens, categorized based on frame type for LS performance.

	Brick Masonry				**Clay Tile**				**All Specimens**			
	Standard Method		Envelop Method		Standard Method		Envelop Method		Standard Method		Envelop Method	
	Ave	Std	**Ave**	Std	**Ave**	Std	**Ave**	Std	**Ave**	Std	**Ave**	Std
Steel Frame	**3.6**	1.6	**3.2**	1.1	**3.8**	2.2	**2.3**	1.8	**3.7**	1.7	**2.8**	1.3
Concrete Frame	**3.9**	1.7	**3.4**	1.6	**3.5**	0.8	**3.4**	0.9	**3.8**	1.6	**3.4**	1.6

to 2.28 for infills in concrete frames.

7. Conclusion

Values of m-factors for infilled frames is investigated in this paper, based on previous experimental studies. It is shown that the first and the third quadrants of the hysteresis curves of each infill specimen give different values for the m-factor, which are both different from the values proposed in common rehabilitation guidelines. A sensitivity analysis is carried out on the influence of aspect ratio, relative stiffness of infill to the frame, etc., on the m-factor. The obtained results are as follows:

- The m-factor of infilled frames depends on infill and frame materials, rather than the infill aspect ratio, and relative stiffness of the frame to the infill (shown by the parameter λ_l).
- Applying the envelope curves normally gives more conservative m-factors for infills, in comparison with the backbone curves proposed in ASCE41[5]. This confirms the new version of the code [6] for using the envelope.
- The first quadrant of the hysteresis curves normally gives greater values for m-factors, compared with the third quadrant.
- The average m-factors of infills in concrete frames are greater than those in steel frames.
- It is suggested to consider m_{LS} of brick and clay tile infill in steel frames as 3.2 and 2.3, respectively. For infills in concrete frames, both of these values are raised to 3.4.
- The modification factor of AAC infills, can be conservatively assumed as 2.3.

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