DAMAGE STATES FOR REINFORCED CMU MASONRY SHEAR WALLS

Jia Li and Terence A. Weigel
Department of Civil Engineering, University of Louisville, Louisville, KY 40292, USA

Abstract

In order to assess the damage loss of reinforced masonry walls under earthquake loading, it is helpful to have a set of commonly accepted damage states. HAZUS gives detailed description for the qualitative damage states and assigns threshold drift ratios for achievement of each damage state. The HAZUS damage states are assigned based on expert opinion and judgment, and performance and experience data. Unfortunately, application of the HAZUS damage states is limited by the fact that they do not differentiate failure mode: flexure, shear and possible mixed flexure/shear. Furthermore, drift ratios defined in HAZUS have not been fully verified by experiment or experience. As a step toward addressing these deficiencies, this paper examines experimental results from three experimental programs and assesses the accuracy of the HAZUS methodology. Drift ratios at achievement of defined damage states are compared with HAZUS definitions. Results show that the HAZUS methodology tends to overestimate the drift ratio achieved by a wall at a given level of damage. In this paper, only experimental results for concrete masonry unit (CMU) walls are considered.

Introduction

Shear walls are the primary lateral load-resisting elements in reinforced masonry structures. When excited seismically, they are usually subjected to simultaneous in-plane loads, out-of-plane loads, axial loads and overturning moments. Design of shear walls for in-plane loads, as well as estimation of damage and associated economic loss upon occurrence of a seismic event, are important issues to all stakeholders: architects, engineers, building officials, insurance companies and owners. A key requirement in establishing a basis for accurate design provisions and assessment of the economic impact of seismic events is having an accurate set of quantitative damage descriptions for critical wall conditions. Also important is a corresponding set of qualitative descriptors that can be related to the quantitative damage descriptions.

A damage state is defined as a specified level of damage under earthquake, corresponding to some critical condition of the wall. Damage states have been defined differently by different agencies / researchers. For example ATC-40 (1996) defines the performance levels (consistent with damage) of Operational, Immediate Occupancy, and Life Safety and Structural Stability. HAZUS (FEMA, 1999) defines four qualitative damage states: slight, moderate, extensive, collapse, as shown in Table 1. HAZUS is software that will estimate potential regional earthquake losses. Loss estimates are used to plan and assist in reduction of risks from earthquakes, and to prepare for pre-earthquake emergency response and post-earthquake recovery. In addition to qualitative damage state, HAZUS also provides quantitative assessment of damage based on drift ratio and a “code level”, as is shown in Table 2. Other quantitative damage indicators used by researchers (Hwang, 2001; Park, 1985; Mander, 1999) include displacement, ductility, energy, restoration time and money. In this paper, the HAZUS damage states are used. Much of this research is done for concrete and may not be directly applicable to the performance of masonry walls.

An issue not addressed by researchers and the HAZUS methodology, at least not directly, is the influence of the mode of response of the wall on the relationship between qualitative and quantitative damage measures. A reinforced masonry wall may respond to a seismic event in a shear critical or

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Table 1. Qualitative definition of damage states in HAZUS.

Damage States	Building Type (RM1L/RM2L*)
Slight	Diagonal hairline cracks on wall surfaces; large cracks around door and window openings in walls with large proportion of openings; minor separation of walls from the floor and roof diaphragms.
Moderate	Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities indicated by larger diagonal cracks. Some walls may have visibly pulled away from the roof.
Extensive	Most shear walls with large openings have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks and visibly buckled wall reinforcement. Partial collapse of the roof may result from failure of wall to diaphragm connections.
Complete	Structure has collapsed or in imminent danger of collapse due to failure of the wall anchorages or the wall panels. Approximately 13(low-rise) of the total area of the building is expected to be collapsed.

*RM1L/RM2L is used to denote low-rise reinforced masonry bearing walls, generally ranging from 1–3 stories, with a total height less than 20 feet.

Table 2. Quantitative definition of damage states in HAZUS.

Seismic Design Level	Building Type (Low-Rise)	Drift Ratio at Damage State Threshold			
		Slight	Moderate	Extensive	Complete
High-Code*	RM1L/RM2L	0.004	0.008	0.024	0.070
Moderate-Code	RM1L/RM2L	0.004	0.007	0.019	0.053
Low-Code	RM1L/RM2L	0.004	0.006	0.016	0.044
Pre-Code	RM1L/RM2L	0.003	0.005	0.013	0.035

*High-Code, Moderate-Code, Low-Code correspond to the "quality" of the design code to which the building was designed. Pre-Code is used to indicate that the building was not designed for seismic loading.

flexurally critical mode. Some walls may exhibit a mixed flexural/shear critical mode. There are other possible response modes (for example, base sliding), but only flexure and shear are considered in this paper.

Flexurally critical walls exhibit yielding of vertical reinforced and crushing of the compression toe as they experience cycles of large excursions of reversed cyclic deformation. Shear critical walls exhibit diagonal tensile cracking when they experience the same type of loading. Examination of Tables 1 and 2 shows that the HAZUS methodology does not differentiate damage states based on behavior mode.

The principal objective of this research is to develop realistic qualitative and quantitative damage states and relate these states to behavior modes. In this paper four damage states are used as found in HAZUS: Slight, Moderate, Extensive, Collapse. The assessment of damage states and their relationship to behavior mode is based on experimental work for in-plane loading done by Shing (1988, 1990), Ibrahim (1999) and Eikanas (2003).

Damage States for Reinforced Masonry Walls

Test Results

Shing tested 16 reinforced concrete masonry walls, each with an aspect ratio of 1. Walls were reinforced both horizontally and vertically, and the amount of reinforcement was varied in order

Table 3. Test results – Shing*.

No	Mode	Str (psi)	ρ_v (%)	ρ_h (%)	Y (k)	Y_d (in)	M (k)	M_d (in)	U (k)	U_d (in)	D (k)	D_d (in)
1(P)	Flexure	200	0.38	0.24	60	0.15	82	0.56	87	0.82	68	1.22
1(N)					N/A	N/A	76	0.35	78	0.59	58	0.85
2(P)	Flexure	270	0.38	0.24	66	0.15	82	0.35	83	0.50	60	0.90
2(N)					N/A	N/A	84	0.50	98	0.54	82	0.90
3(P)	Shear	270	0.74	0.14	N/A	N/A	80	0.17	100	0.60	93	0.92
3(N)					N/A	N/A	N/A	N/A	105	0.70	80	1.10
4(P)	Shear	0	0.74	0.14	65	N/A	55	0.17	72	0.34	N/A	N/A
4(N)					N/A	N/A	51	0.12	87	0.48	N/A	N/A
5(P)	Shear	100	0.74	0.14	82	0.35	60	0.16	89	0.40	70	0.46
5(N)					N/A	N/A	N/A	N/A	84	0.40	65	0.80
7(P)	Shear	100	0.74	0.14	83	0.25	65	0.15	97	0.45	N/A	N/A
7(N)					N/A	N/A	60	0.10	97	0.61	72	0.73
9(P)	Shear	270	0.38	0.14	76	0.10	92	0.30	96	0.30	80	0.35
9(N)					N/A	N/A	N/A	N/A	96	0.30	N/A	N/A
10(P)	Mixed	100	0.38	0.14	48	0.10	60	0.15	69	0.80	60	0.85
10(N)					N/A	N/A	58	0.18	67	0.85	64	1.15
12(P)	Flexure	100	0.38	0.24	46	0.10	69	0.38	71	0.62	70	0.92
12(N)					N/A	N/A	70	0.57	71	0.87	66	1.10
13(P)	Shear	270	0.54	0.24	90	0.17	109	0.30	109	0.40	98	0.70
13(N)					N/A	N/A	115	0.50	115	0.64	N/A	N/A
14(P)	Shear	270	0.54	0.14	85	0.12	98	0.25	98	0.40	95	0.58
14(N)					N/A	N/A	105	0.32	112	0.40	80	0.50
15(P)	Mixed	100	0.54	0.24	60	0.19	67	0.25	82	0.55	66	1.30
15(N)					N/A	N/A	80	0.30	88	0.55	84	1.20
16(P)	Shear	270	0.74	0.24	100	0.20	87	0.14	120	0.60	105	0.70
16(N)					N/A	N/A	85	0.15	120	0.55	N/A	N/A

*See the Appendix for explanation of table notation.

to produce either shear dominated or flexurally dominated response. A summary of Shing's test results are shown in Table 3. Of Shing's walls, specimens 1, 2, 10, 12 and 15 exhibited primarily flexural response (10 and 15 actually exhibited mixed response) and specimens 3, 4, 5, 7, 9, 13, 14 and 16 exhibited shear response. Shing's specimens 6, 8, and 11 exhibited significant base sliding and results for those walls are not included in this paper.

Eikanas tested seven reinforced concrete masonry walls. Aspect ratios varied from 1.0 to 2.63. Walls were reinforced both horizontally and vertically and the amount of reinforcement was varied from wall to wall. All of Eikanas's walls exhibited primarily flexurally critical behavior. A summary of Eikanas's test results are shown in Table 4.

Ibrahim tested five reinforced concrete masonry walls. The walls were all 55 in tall and aspect ratios varied from 0.467 to 1.00. Walls were reinforced both horizontally and vertically. All of Ibrahim's walls exhibited shear critical behavior. A summary of Ibrahim's test results are shown in Table 5.

Table 4. Test results – Eikanas.

No	AR	Str (psi)	ρ_v (%)	ρ_h (%)	Y (k)	Y_d (in)	S (k)	S_d (in)	U (k)	U_d (in)	D (k)	D_d (in)
1(P)	1.29	27	0.29	0.18	27.2	0.10	36.0	0.16	49.7	0.73	45.1	1.12
1(N)					28.1	0.11	40.4	0.31	47.6	0.90	39.0	1.15
2(P)	1.87	27	0.29	0.18	9.9	0.19	8.5	0.13	29.7	1.58	29.4	1.99
2(N)					25.1	0.37	31.6	0.58	35.1	0.99	28.0	1.65
3(P)	2.63	27	0.31	0.18	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3(N)					4.5	0.48	2.9	0.19	18.9	3.19	18.7	5.00
4(P)	1.29	27	0.51	0.18	35.8	0.16	47.9	0.28	64.8	0.57	49.8	0.69
4(N)					41.2	0.34	50.1	0.50	53.6	0.70	41.3	0.90
5(P)	1.87	27	0.51	0.18	21.5	0.28	30.9	0.38	46.2	0.99	36.8	1.38
5(N)					26.1	0.28	34.3	0.53	45.3	1.19	33.8	1.78
6(P)	2.63	27	0.52	0.18	13.7	0.23	20.7	0.48	25.3	1.12	20.8	2.24
6(N)					15.2	0.25	23.3	0.75	25.6	1.13	18.3	1.81
7(P)	1.00	27	0.29	0.18	45.7	0.08	60.5	0.20	75.3	0.50	57.6	0.70
7(N)					38.1	0.11	49.7	0.20	64.3	0.50	50.6	0.80

Table 5. Test results – Ibrahim.

No	AR	Str (psi)	ρ_v (%)	ρ_h (%)	Y (k)	Y_d (in)	M (k)	M_d (in)	U (k)	U_d (in)	D (k)	D_d (in)
1(P)	1.000	100	0.4	0.2	34.4	0.13	38.6	0.23	44.9	0.31	40.4	0.59
1(N)					34.4	0.15	37.3	0.17	47.0	0.59	30.8	0.79
2(P)	0.636	100	0.4	0.2	56.4	0.16	56.8	0.20	83.1	0.59	N/A	N/A
2(N)					61.6	0.13	64.3	0.16	91.7	0.39	76.4	0.59
3(P)	0.467	100	0.4	0.2	106.5	0.16	108.3	0.18	124.3	0.39	N/A	N/A
3(N)					118.2	0.16	116.4	0.16	118.9	0.26	101.1	0.39
4(P)	0.636	100	0.6	0.2	81.3	0.15	85.2	0.18	93.3	0.22	73.0	0.63
4(N)					79.5	0.16	74.4	0.20	91.9	0.31	67.4	0.59
5(P)	0.636	250	0.4	0.2	75.0	0.10	75.7	0.12	78.0	0.26	62.9	0.59
5(N)					80.0	0.12	92.6	0.16	105.2	0.31	73.0	0.59

Qualitative Damage States

Because HAZUS fails to differentiate between flexurally critical and shear critical walls, it was necessary to create such a distinction when evaluating test results. Table 6 shows the classification selected.

For flexurally dominated behavior, initial yielding of flexural steel is associated with “Slight” damage. For this damage state repairs can be made relatively easily by grout injection and/or cosmetic repairs. The value of masonry strain used to define the end of the “Moderate” damage region (0.0025) is based on what the MSJC Code (2005) calls the “maximum usable strain”.

Table 6. Qualitative definition of damage states based on experimental results.

Damage States	Flexurally Dominated Behavior	Shear Dominated Behavior
Slight	First yield of vertical steel achieved	First yield of vertical steel achieved
Moderate	Masonry compressive strain 0.0025 achieved	Major diagonal cracking
Extensive	Toe crushing or ultimate load achieved	Ultimate load achieved
Complete	20% load degradation	20% load degradation

For shear dominated behavior, major diagonal cracks extend at an angle of approximately 45°, from the top of the wall toward its base. When large amounts of flexural reinforcement are provided, the vertical steel may not yield, and the first indication of damage will be diagonal cracking, and the wall enters the "Moderate" damage state after vertical steel yielding. Shing's specimens 5, 7, and 16 exhibited this type of behavior.

"Complete" damage is defined as 20% strength degradation. Although collapse may not occur at load degradation of 20% (or larger), repair costs will typically be such that the structure is classified as a total economic loss. Therefore the load degradation of 20% or larger is be considered "Complete" damage.

Quantitative Damage States

In order to compare directly with HAZUS methodology, drift ratio is used as the quantitative damage indicator. Tables 7 through 9 show measured drift ratio (DR) from experimental results.

Parameters that influence the behavior mode of a reinforced masonry wall include aspect ratio, amount of flexural steel, amount of shear steel and masonry strength. HAZUS methodology presented in this paper focuses on low-rise masonry bearing walls. Most of the walls tested in the three experimental programs had axial loads consistent with low-rise construction. One of Ibrahim's walls had an axial load of 250 psi and some of Shing's walls (see Table 3) had axial loads of 200 or 270 psi. These levels of axial load would be consistent with medium-rise or high-rise construction. Despite this inconsistency between axial load used in some of the experimental tests and the low-rise HAZUS methodology used in this paper, axial load is not considered as a parameter in this study. Future work may incorporate effects of axial load in damage assessment.

For the experimental database examined, walls with aspect ratio less than 1 exhibited shear critical response, regardless of the amount of reinforcement present. The specimens falling in this category are 2, 3, 4 and 5 from Ibrahim's test program.

When the aspect ratio was greater than or equal to 1, behavior can be either flexurally critical, shear critical or mixed mode. Ibrahim's Wall 1 had an aspect ratio of 1, and exhibited shear critical behavior. All of Shing's walls had an aspect ratio of 1. His Walls 1, 2, 10, 12 and 15 exhibited primarily flexural response (10 and 15 actually exhibited mixed response) and specimens 3, 4, 5, 7, 9, 13, 14 and 16 showed shear critical behavior. The specific behavior mode depended on the amount of flexural and shear reinforcing present in the wall. All of Eikanas's walls exhibited flexural response.

Drift ratio versus the corresponding damage states are plotted in Figure 1. The flexurally critical specimens ($1.0 < AR < 2.6$, $AR = 1.0$) and shear critical specimens ($AR = 1.0$, $AR < 1.0$) are plotted separately. In these figures, numerical designations 1, 2, 3, 4 correspond to damage states Slight, Moderate, Extensive and Collapse, respectively.

In Figure 1, the aspect ratio (AR) is used as a discriminator. The aspect ratio is defined as the ratio of wall height divided by wall length, without regard to wall support conditions. Some

Table 7. Drift ratio – Shing.

No	H (in)	Y_d (in)	DR	Avg	M_d (in)	DR	Avg	U_d (in)	DR	Avg	D_d (in)	DR	Avg
1(P)	72	0.15	0.21	0.21	0.56	0.78	0.64	0.82	1.14	0.98	1.22	1.69	1.44
1(N)		N/A	N/A		0.35	0.49		0.59	0.82		0.85	1.18	
2(P)	72	0.15	0.21	0.21	0.35	0.49	0.59	0.50	0.69	0.72	0.90	1.25	1.25
2(N)		N/A	N/A		0.50	0.69		0.54	0.75		0.90	1.25	
3(P)	72	N/A	N/A	N/A	0.17	0.24	0.24	0.60	0.83	0.90	0.92	1.28	1.41
3(N)		N/A	N/A		N/A	N/A		0.70	0.97		1.10	1.53	
4(P)	72	N/A	N/A	N/A	0.17	0.24	0.21	0.34	0.47	0.57	N/A	N/A	N/A
4(N)		N/A	N/A		0.12	0.17		0.48	0.67		N/A	N/A	
5(P)	72	0.35	0.49	0.49	0.16	0.22	0.22	0.40	0.56	0.56	0.46	0.64	0.88
5(N)		N/A	N/A		N/A	N/A		0.40	0.56		0.80	1.11	
7(P)	72	0.25	0.35	0.35	0.15	0.21	0.18	0.45	0.63	0.74	N/A	N/A	1.01
7(N)		N/A	N/A		0.10	0.14		0.61	0.85		0.73	1.01	
9(P)	72	0.10	0.14	0.14	0.30	0.42	0.42	0.30	0.42	0.42	0.35	0.49	0.49
9(N)		N/A	N/A		N/A	N/A		0.30	N/A		N/A	N/A	
10(P)	72	0.10	0.14	0.14	0.15	0.21	0.23	0.80	1.11	1.15	0.85	1.18	1.39
10(N)		N/A	N/A		0.18	0.25		0.85	1.18		1.15	1.60	
12(P)	72	0.10	0.14	0.14	0.38	0.53	0.66	0.62	0.86	1.03	0.92	1.28	1.41
12(N)		N/A	N/A		0.57	0.79		0.87	1.20		1.10	1.53	
13(P)	72	0.17	0.24	0.24	0.30	0.42	0.56	0.40	0.56	0.73	0.70	0.97	0.97
13(N)		N/A	N/A		0.50	0.69		0.64	0.89		N/A	N/A	
14(P)	72	0.12	0.17	0.17	0.25	0.35	0.40	0.40	0.56	0.56	0.58	0.81	0.75
14(N)		N/A	N/A		0.32	0.44		0.40	0.56		0.50	0.69	
15(P)	72	0.19	0.26	0.26	0.25	0.35	0.39	0.55	0.76	0.76	1.30	1.81	1.74
15(N)		N/A	N/A		0.30	0.42		0.55	0.76		1.20	1.67	
16(P)	72	0.20	0.28	0.28	0.14	0.19	0.20	0.60	0.83	0.80	0.70	0.97	0.97
16(N)		N/A	N/A		0.15	0.21		0.55	0.76		N/A	N/A	

researchers define an "effective" aspect ratio, which, for example, would be calculated as half the wall height divided by its length, when fixed-fixed support conditions exist. However, in order to keep the quantitative classification simple, and because the current experimental database is limited in size, only the aspect ratio is used in Figure 1.

Based on experimental results and results shown in Figure 1, quantitative damage states are classified as shown in Table 10.

Results Compared with HAZUS

From Table 10 we observe that comparable levels of damage will be produced at much lower drift ratios when the wall behavior is dominated by shear, as opposed to flexure. This implies that a basing damage estimates on a single drift ratio for all low-rise masonry walls, as does HAZUS, is not likely to be particularly accurate.

Table 8. Drift ratio – Eikanas.

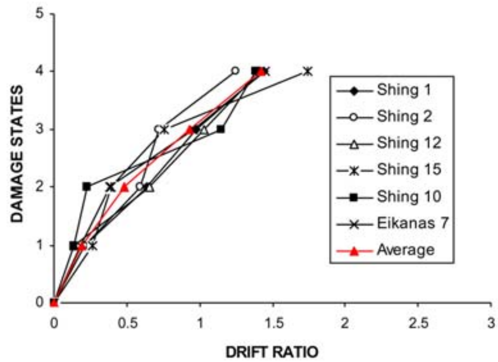
No	H (in)	Y_d (in)	DR	Avg	S_d (in)	DR	Avg	U_d (in)	DR	Avg	D_d (in)	DR	Avg
1(P)	52	0.10	0.19	0.20	0.16	0.31	0.46	0.73	1.40	1.57	1.12	2.15	2.18
1(N)		0.11	0.21		0.31	0.60		0.90	1.73		1.15	2.21	
2(P)	84	0.19	0.23	0.34	0.13	0.15	0.42	1.58	1.88	1.53	1.99	2.36	2.16
2(N)		0.37	0.44		0.58	0.69		0.99	1.18		1.65	1.96	
3(P)	84	N/A	N/A	0.57	N/A	N/A	0.22	N/A	N/A	3.80	N/A	N/A	5.95
3(N)		0.48	0.57		0.19	0.22		3.19	3.80		5.00	5.95	
4(P)	52	0.16	0.31	0.48	0.28	0.54	0.75	0.57	1.10	1.24	0.69	1.33	1.53
4(N)		0.34	0.65		0.50	0.96		0.70	1.35		0.90	1.73	
5(P)	84	0.28	0.33	0.33	0.38	0.45	0.54	0.99	1.18	1.30	1.38	1.64	1.88
5(N)		0.28	0.33		0.53	0.63		1.19	1.42		1.78	2.12	
6(P)	84	0.23	0.27	0.29	0.48	0.57	0.73	1.12	1.33	1.34	2.24	2.67	2.41
6(N)		0.25	0.30		0.75	0.89		1.13	1.35		1.81	2.15	
7(P)	52	0.08	0.15	0.18	0.20	0.38	0.38	0.50	0.96	0.96	0.70	1.35	1.45
7(N)		0.11	0.21		0.20	0.38		0.50	0.96		0.80	1.54	

Table 9. Drift ratio – Ibrahim.

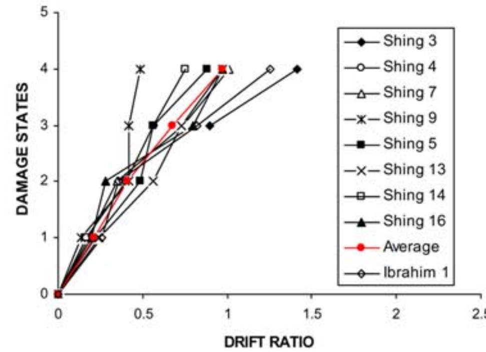
No	H (in)	Y_d (in)	DR	Avg	M_d (in)	DR	Avg	U_d (in)	DR	Avg	D_d (in)	DR	Avg
1(P)	55	0.13	0.24	0.26	0.23	0.41	0.36	0.31	0.57	0.82	0.59	1.07	1.25
1(N)		0.15	0.27		0.17	0.30		0.59	1.07		0.79	1.43	
2(P)	55	0.16	0.29	0.27	0.20	0.36	0.33	0.59	1.07	0.89	N/A	N/A	1.07
2(N)		0.13	0.24		0.16	0.29		0.39	0.71		0.59	1.07	
3(P)	55	0.16	0.29	0.29	0.18	0.32	0.31	0.39	0.71	0.59	N/A	N/A	0.71
3(N)		0.16	0.29		0.16	0.29		0.26	0.46		0.39	0.71	
4(P)	55	0.15	0.27	0.28	0.18	0.32	0.34	0.22	0.39	0.48	0.63	1.14	1.10
4(N)		0.16	0.29		0.20	0.36		0.31	0.57		0.59	1.07	
5(P)	55	0.10	0.18	0.20	0.12	0.21	0.25	0.26	0.46	0.52	0.59	1.07	1.07
5(N)		0.12	0.21		0.16	0.29		0.31	0.57		0.59	1.07	

Table 10. Quantitative damage states.

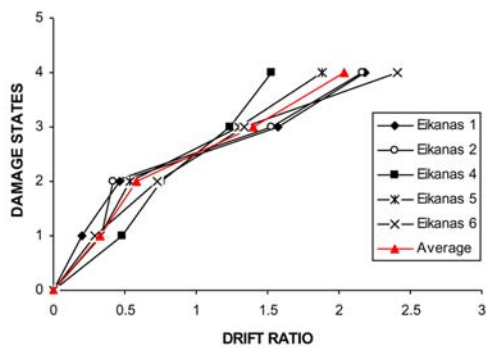
Damage States	Flexurally Dominated Behavior		Shear Dominated Behavior	
	Drift Ratio (AR = 1.0)	Drift Ratio (1.0 < AR < 2.6)	Drift Ratio (AR = 1.0)	Drift Ratio (AR < 1.0)
Slight	<0.25	0.20–0.50	<0.25	0.20–0.30
Moderate	0.25–0.70	0.40–0.80	0.25–0.55	0.25–0.35
Extensive	0.70–1.20	1.20–1.60	0.55–0.80	0.40–1.00
Complete	1.10–1.75	1.50–2.40	0.80–1.50	1.00–1.25



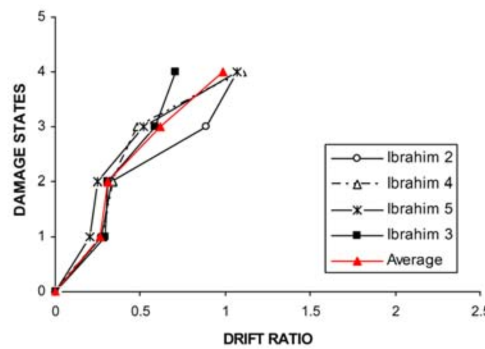
(a) Flexurally critical behavior (AR = 1.0)



(b) Shear critical behavior (AR = 1.0)



(c) Flexurally critical behavior (1.0 < AR < 2.6)



(d) Shear critical behavior (AR < 1.0)

Fig. 1. Drift ratio versus damage states.

Table 11. Drift ratio comparison with HAZUS.

Damage States	HAZUS				Flexure		Shear	
	High-Code	Moderate-Code	Low-Code	Pre-Code	AR = 1.0	1.0 < AR < 2.6	AR = 1.0	AR < 1.0
Slight	0.40	0.40	0.40	0.30	<0.25	0.20–0.50	<0.25	0.20–0.30
Moderate	0.80	0.70	0.60	0.50	0.25–0.70	0.40–0.80	0.25–0.55	0.25–0.35
Extensive	2.40	1.90	1.60	1.30	0.70–1.20	1.20–1.60	0.55–0.80	0.40–1.00
Complete	7.00	5.30	4.40	3.50	1.10–1.75	1.50–2.40	0.80–1.50	1.00–1.25

Table 11 compares HAZUS drift ratios with those selected in this paper, as discriminated by qualitative damage state. Note that HAZUS predicts much larger drift ratios than do experimental results. The difference is quite high in the Extensive and Complete damage states. Current HAZUS methodology compares best with high aspect ratio, flexurally-critical walls.

Conclusions

In this study, quantitative and qualitative damage states for low-rise reinforced masonry walls are defined based on experimental results. Drift ratio is used as the quantitative damage indicator, and separate classifications are provided depending on whether the behavior of the wall is dominated by flexure or by shear. Comparison of the drift ratios selected in this paper indicates large differences when compared to the HAZUS methodology, which does not differentiate based on wall behavior mode. Current HAZUS provisions best correlate with high aspect ratio, flexurally critical walls.

While it is certain that masonry wall damage is significantly influenced by behavior mode, limitations of the experimental database restrict the confidence that can be place in any classification system. Although the authors do believe classification system presented in this paper is superior to the current HAZUS methodology, more testing is required before any classification system can be made reliable.

Appendix

No.	= specimen number
(P)	= value in positive test direction
(N)	= value in negative test direction
AR	= aspect ratio
H	= wall height, in
DR	= drift ratio, %
Avg	= average drift ratios in positive and negative directions
ρ_v	= wall vertical steel, %
ρ_h	= wall horizontal steel, %
Y	= lateral load at first yield of vertical steel, k
Y_d	= wall displacement at Y, in
M	= lateral load at major diagonal crack, k
M_d	= wall displacement at M, in
S	= lateral load when masonry achieved compression strain of 0.0025, k
S_d	= wall displacement at S, in
U	= maximum lateral load attained, k
U_d	= wall displacement at U, in
D	= lateral load at 20% degradation, k
D_d	= wall displacement at D, in
Str	= axial stress, psi
N/A	= value is not available

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