SEISMIC BEHAVIOR OF AAC STRUCTURES DESIGNED WITH DIFFERENT FLEXURAL CAPACITIES

J.L. Varela[1], M.R. Bagundo[2] and L.E. Fernandez[1]

[1] *Professor, College of Engineering , Autonomous University of Yucatan, Merida, Mexico*
[2] *Former graduate student, College of Engineering, Autonomous University of Yucatan, Merida, Mexico*
Email: vrivera@uady.mx and luis.fernandez@uady.mx

ABSTRACT :

The behavior of three structures of autoclaved aerated concrete (AAC) designed with different force-reduction factors is evaluated in terms of maximum displacement ductility and drift ratio demands. The maximum demands are obtained from nonlinear analyses carried out using earthquake ground motions, representative of the Mexico City firm soil, together with hysteretic models obtained from laboratory tests results. Earthquake ground motions were scaled by making the corresponding response spectra to represent in average the design spectrum. Based on the nonlinear analyses results and assuming a maximum displacement ductility capacity of 3.5, a value of the force-reduction factor of 1.5 and a value of the displacement amplification factor of 2.0 are obtained. It is concluded that those values are adequate for the seismic design of the AAC structures studied.

KEYWORDS: Autoclaved aerated concrete, force-reduction factor, displacement-amplification factor, nonlinear analysis, displacement ductility

1. INTRODUCTION

Autoclaved aerated concrete (AAC) is a lightweight cellular material composed of Portland cement, lime, finely ground sand, water, and an expansive agent. AAC structural elements are mainly shear walls and floor diaphragms. Shear walls may be constructed using AAC modular blocks or panels, and floor diaphragms using floor panels. Individual AAC units are bonded together using thin-bed mortar joints approximately 1.5 mm thick. Properties of AAC blocks are specified in ASTM C1386 (1998) and properties of AAC panels in ASTM C1452 (2000).

The design and construction of AAC structures in Mexico is mainly for low seismic zones. In Mexico City, the design of those structures is limited because its current seismic code does not prescribe explicit values for the force-reduction factor for AAC structures; therefore, those structures have to be designed elastically. Several research studies have shown that the force-reduction factor for any structure should be based on displacement ductility, natural period of the structure, soil conditions, structural overstrength, and characteristics of earthquakes, among others (Miranda y Bertero, 1994, Uang, 1991, and Nassar and Krawinkler, 1991). For the case of structures in firm soils, The Mexico city seismic code (Gaceta Oficial del D.F., 2004) allows the reduction of the seismic forces by a force-reduction factor (Q’). The seismic forces prescribed for firm soils in Mexico City are already reduced to account for overstrength; therefore, the force-reduction factor (Q’) is intended to account for the amount of ductility in the structure (Rosenblueth and Gómez, 1987). The objective of this paper is to evaluate the nonlinear behavior of AAC shear-wall structures subjected to earthquake ground motions representative of Mexico City firm soils. The AAC structures are designed with different flexural capacities to determine appropriate force-reduction and displacement-amplification factors for those structures. The procedure used in this work is based on that proposed by Varela et al., 2006. The procedure is adapted for the case of the Mexico City Seismic Code.

1. GENERAL PROCEDURE TO PROPOSED FORCE REDUCTION FACTORS

The procedure used to select force-reduction factors for the AAC structures studied is the following: (1) Select an AAC structure. (2) Analyze the AAC structure using the modal analyses procedure specified in the Mexico City Seismic Code. The elastic global drift ratio of the structure should be less or equal to 1%, and the flexural capacity of the walls equal to the bending moments obtained from the elastic analyses (Q' = 1). (3) Select an earthquake from a suite of earthquakes representing the corresponding design spectrum. (4) Select a value of Q' greater than one, and redesign the structure for a reduced flexural capacity. For example, if Q' is selected as 2, then the required flexural capacity is reduced by a factor of 2. (5) Run a dynamic nonlinear analysis and calculate the drift ratio and displacement ductility demands. If the drift ratio demand is equal to 1%, the value of Q' assumed is the critical value of Q' based on drift ratio; similarly, if the displacement ductility demand is equal to 3.5, the assumed value of Q' is the critical value based on displacement ductility. (6) Repeat for other earthquakes of the same suite, and AAC shear wall structures. The general procedure for selecting values of the factor Q' is presented as a flow chart in Figure 1.

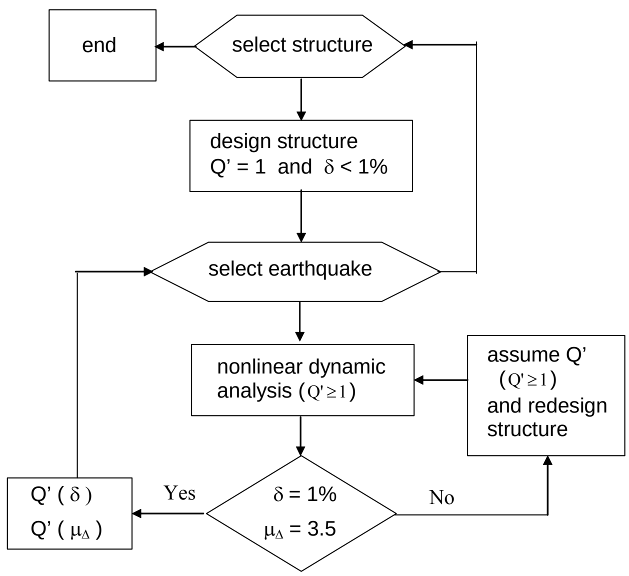

Figure 1 General procedure for selecting the factor Q'

2.1. Selection and design of structures

Three AAC shear wall structures were selected for evaluation under earthquakes representative of the Mexico City firm soil. The structures were selected as AAC shear-wall structures because shear walls are the major AAC structural elements resisting seismic forces. The AAC structures selected were a three-, four- and five-story cantilever-wall structures. Typical wall dimensions of 6.1 m long, 3 m high, and 0.25 m thick were used in every story of each structure. Slabs were made of AAC roof panels of 0.25 m thick. AAC-6 strength class was assumed for each structure.

The structures were modeled as planar structures. A tributary width of 6.1 m was assumed to calculate the weights of each story. Design spectrum was that corresponding to the Mexico City firm soil. Modal elastic analyses were carried out using the program SAP2000 (Computers and Structures, Inc., 2000), with a reduced initial stiffness consistent with that used in the nonlinear analyses as presented later. Flexural capacities of walls are assumed equal to the bending moments obtained from the elastic modal analyses as described in the procedure to select the factor Q'. Actual bar sizes for flexural reinforcement are not selected, to avoid introducing element overstrength. Table 1 shows the natural period (T_n), base shear and bending moment at the base of the walls calculated from the modal analysis procedure for each selected structure.

Table 1 Natural period, base shear and bending moments for each selected structure

Structure	T_n (sec)	Base shear (kN)	Bending moment (kN-m)
3-story	0.25	73.60	509.20
4-story	0.40	95.03	854.66
5-story	0.58	116.80	1,288.80

2.2. Selection and scaling of earthquakes

A suite of ten earthquakes representative of the firm soils of Mexico City were selected from the Mexican Strong Motion Data Base (SMIS, 2000). The selection of earthquakes was based on those with peak ground accelerations (a_{max}) greater than 4 gals and with magnitudes greater than 5 (Reinoso and Ordaz, 1999). Earthquakes from different dates and locations were included as presented in Table 2. The selected suite of earthquakes was scaled to represent the design seismic forces. Acceleration response spectra were calculated for the suite of earthquakes and compared with the corresponding design spectrum for firm soils. The entire suite was scaled using a single scaling factor calculated as follows: (1) calculate the elastic response spectra for the suite of earthquakes; (2) calculate the mean spectral accelerations of the response spectra for periods of 0.25, 0.40 and 0.58 seconds which represent the natural periods of the structures studied; (3) calculate a scaling factor for each period as the design spectral acceleration divided by the average spectral acceleration; (4) the final single scaling factor is the average of the three scaling factors calculated in Step 3, for this case the single scaling factor was equal to 18.6. The scaled response spectra for the selected suite of earthquakes together with the corresponding design spectrum are presented in Figure 2.

Table 2 Selected suite of earthquakes

Earthquake	ID	date	a_{max} (gals)	soil type
CUP1-94-05-23-C3	S1	23/05/94	5.26	rock
CUP1-94-12-10-C3	S2	10/12/94	5.98	rock
CUP3-90-05-31-C3	S3	31/05/90	5.14	rock
CUP3-93-10-24-C2	S4	24/10/93	4.31	rock
CUP4-96-07-15-C3	S5	15/07/96	4.22	rock
CUP4-97-01-11-C3	S6	11/01/97	5.86	rock
TE07-94-12-10-C3	S7	10/12/94	3.93	firm soil
TE07-97-01-11-C1	S8	11/01/97	4.21	firm soil
TP13-90-05-31-C1	S9	31/05/90	5.11	firm soil
TP13-93-10-24-C1	S10	24/10/93	3.99	firm soil

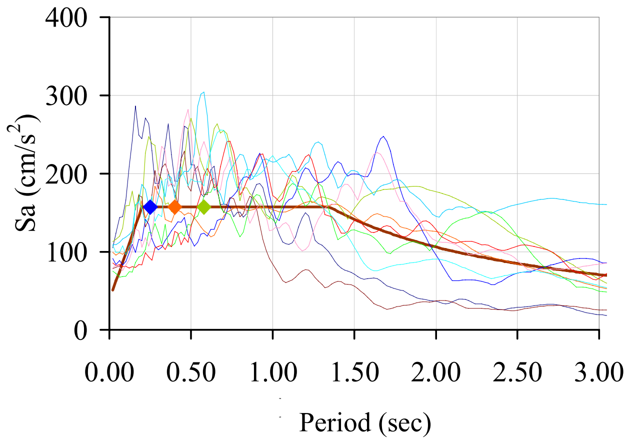

Figure 2 Scaled response spectra and corresponding design spectrum

2.3. Nonlinear analysis

In this study, the nonlinear analysis program CANNY 99 (Kangning Li, 1999) was selected to evaluate the performance of the AAC shear-wall structures subjected to different earthquake ground motions. Structures in that program are idealized as rigid nodes connected by line elements and springs. All structural elements are treated as massless line elements represented by their centroidal axes, with mass concentrated at the nodes or at the center of gravity of floors. The idealized wall element of that program considers the wall as a line element located at the wall centerline. The wall element is idealized using two nonlinear flexural springs, two rigid links, one nonlinear shear spring and one axial spring. The nonlinear flexural springs are located at the top and bottom of the wall centerline. Therefore, all nonlinearity is concentrated at the wall ends (lumped nonlinearity). The three- , four- and five-story cantilever-wall structures were modeled using three, four and five idealized wall elements respectively.

The hysteretic model selected to represent the behavior of the nonlinear flexural and shear springs was the CANNY CA7 model (Kangning Li, 1999) which uses user-input hysteretic parameters to define the loading and unloading branches, degradation of strength and stiffness, and pinching of the hysteretic loops. The behavior of the nonlinear flexural spring is defined by a bilinear moment-rotation curve and the nonlinear shear spring by a bilinear force-displacement curve. The behavior of the axial spring was defined by the elastic model EL1 of the program CANNY 99.

The hysteretic curve of the nonlinear flexural spring was defined as follows (Varela et al. 2006): (1) the initial stiffness is defined using the modulus of elasticity of AAC and a reduced moment of inertia equal to 40% of the gross moment of inertia of the wall; (2) the post-yielding stiffness is selected as 1% of the initial stiffness; and (3) the degradation of the unloading stiffness is defined using a hysteretic parameter θ of 1 (Kangning Li, 1999). The hysteretic curve of the nonlinear shear spring was defined as follows (Varela et al., 2006): (1) the initial stiffness is defined using the shear modulus of AAC and a reduced area equal to 40% of the gross area of the wall; (2) the stiffness after shear cracking is selected as 1% of the initial stiffness; (3) the degradation of the unloading stiffness is defined using a hysteretic parameter θ of 1; and (4) the degradation of the shear strength is defined using a hysteretic parameter λ_u of 0.3 and λ_e of 0 (Kangning Li, 1999). Pinching of the hysteretic loops is not included because this phenomenon was not observed in all the shear-dominated walls.

3. VALUES OF THE FORCE-REDUCTION FACTOR (Q')

The procedure described above to select the force-reduction factor (Q') was carried out for the three selected AAC shear-wall structures using the selected suite of earthquakes representative of the Mexico City firm soil. In most cases values of Q' of 1, 1.5, 2 and 2.5 were assumed in the proposed procedure. The displacement ductility demands associated to different values of Q' for the three-, four- and five-story structures are presented in Table 3, Table 4 and Table 5, respectively.

Table 3 Displacement ductility demands for the AAC three-story structure

Q'	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1.00	1.44	1.73	1.00	1.00	1.00	1.11	1.00	1.00	1.16	1.00
1.50	2.83	2.72	2.15	1.27	2.98	3.57	1.50	1.00	2.09	1.24
2.00	4.97	15.03	5.42	1.88	5.90	16.02	3.17	1.32	3.38	11.51
2.50	--	--	--	4.60	--	--	5.06	15.17	5.33	--

Table 4 Displacement ductility demands for the AAC four-story structure

Q'	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1.00	1.21	1.00	1.00	1.00	1.14	1.00	1.00	1.00	1.00	1.37
1.50	2.52	4.97	2.03	1.32	2.40	4.79	1.16	1.00	2.57	3.55
2.00	6.18	--	3.59	2.41	3.93	--	2.28	5.87	5.09	3.73
2.50	--	--		4.98	--	--	6.84	--	--	--

Table 5 Displacement ductility demands for the AAC five-story structure

Q'	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1.00	1.00	1.57	1.00	1.00	1.00	1.53	1.13	1.45	1.44	1.51
1.50	2.40	3.32	1.00	1.57	1.73	3.86	1.93	4.30	2.78	2.98
2.00	3.19	5.94	2.60	4.64	2.95	--	3.23	--	4.49	3.61
2.50	4.25	--	5.61	--	4.17	--	--	--	--	--

Table 3, Table 4 and Table 5 show that the displacement ductility demands are in general greater than the corresponding assumed value of the force-reduction factor (Q'). That difference increases as the assumed value of Q' increases.

The proposed procedure for selecting the force reduction factor (Q') is based on a maximum drift ratio and displacement ductility capacity. The main objective on including drift and ductility capacities is to provide reasonable limits to avoid collapse of AAC shear-wall structures during severe earthquake ground motions. The drift ratio capacity is considered to limit damage and differential movement in AAC shear-wall structures, and the displacement ductility capacity to control the amount of inelastic deformation in those structures.

The maximum drift ratio and displacement ductility capacities used in this work are based on the drift ratios and displacement ductilities observed from six AAC flexure-dominated specimens (Varela et al., 2006). Those specimens were tested under simulated gravity loads plus quasi-static reversed cyclic lateral loads representing the effects of strong ground motions (Varela et al., 2006). The aspect ratio and normalized axial force variations of the specimens represent in general those expected in potential walls of AAC shear-wall structures up to five stories high (Varela et al., 2006).

Linear interpolation was used among values of Table 3, Table 4 and Table 5 to calculate critical values of Q', defined in this work as those values of Q' that make the global drift ratio and displacement ductility demands equal to the maximum global drift ratio and displacement ductility capacities (Table 6). In all cases the critical value of Q' based on displacement ductility was smaller than that based on global drift ratio.

Table 6 Critical values of Q' for the AAC structures studied

Structure	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Average
3-story	1.55	1.75	1.70	2.37	1.60	1.50	2.10	2.17	1.75	1.71	1.82
4-story	1.63	1.25	2.00	2.43	1.90	1.29	2.12	1.90	1.75	1.45	1.77
5-story	2.20	1.55	2.20	1.80	2.30	1.48	2.10	1.40	1.70	2.00	1.87

Table 6 shows that the average values of Q' are in general similar for the three AAC shear-wall structures studied. Based on those average values, a value of Q' of 1.5 seems reasonable for those AAC structures designed on firm soils of Mexico City. The value of Q' of 1.5 corresponds to a value of the seismic behavior factor (Q) of 1.5 (Gaceta Oficial del D.F., 2004) because the natural periods of the AAC structures studied are located in the flat part of the design spectrum.

For structures in the Mexico City firm soil the expected maximum displacement during a severe earthquake is calculated as the product of the elastic displacement calculated using reduced forces, and the seismic behavior factor (Q).

Independent displacement-amplification factors were calculated for each structure and earthquake studied.

Those independent factors were defined as the ratio of the maximum nonlinear displacement (Δ_{max}) and the elastic displacement (Δ_y) calculated using reduced forces. The maximum nonlinear displacements were obtained from nonlinear analyses carried out using a value of Q' equal to 1.5; the elastic displacements were obtained from the modal elastic analyses carried out using a value of Q' equal to 1.5. Table 7 shows the values of the independent displacement-amplification factors obtained for the structures and earthquakes studied.

Table 7 Independent displacement-amplification factors for the AAC structures studied

Structure	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Average
3-story	2.61	2.28	1.90	1.13	2.07	2.89	1.33	0.82	1.98	1.13	1.82
4-story	2.41	4.32	1.78	1.22	2.17	4.63	1.11	1.33	2.53	3.55	2.51
5-story	2.25	2.60	1.42	1.43	1.56	3.27	1.86	3.95	2.51	2.87	2.37

Table 7 shows that the average values of the displacement-amplification factors are greater than the value of the force-reduction factor (Q') of 1.5 selected in this work. This means that a greater value of needs to be used to estimate the maximum displacement during a severe earthquake. In this work a value of 2 is recommended as a displacement- amplification factor for the AAC structures studied.

3. FINAL CONCLUSIONS

Based on the nonlinear behavior of three AAC shear-wall structures subjected to different earthquake ground motions representative of the Mexico City firm soils, a value of the force-reduction factor of 1.5 and a value of the displacement-amplification factor of 2 are adequate for the seismic design of those structures.

REFERENCES

ASTM C 1386 (1998): "Standard Specification for Precast Autoclaved Aerated Concrete (PAAC) Wall Construction Units", American Society for Testing and Materials, West Conshohocken, PA.

ASTM C1452 (2000). "Standard Specification for Reinforced Autoclaved Aerated Concrete Elements", American Society for Testing and Materials, West Conshohocken, PA.

Computers and Structures, Inc. (2000). SAP2000 Nonlinear V7.10, 1999, Computers and Structures, Inc., Berkeley, California.

Gaceta Oficial del D. F. (2004), "Normas Técnicas Complementarias para Diseño por Sismo", Mexico.

Kangning Li (1999). "A 3-Dimensional Nonlinear Static / Dynamic Structural Analysis Program", CANNY Structural, Vancouver, Canada.

Miranda, E. and Bertero, V. (1994). "Evaluation of Strength Reduction Factors for Earthquake-Resistant Design", Earthquake Spectra, Earthquake Engineering Research Institute, Vol. 10, No. 2, pp. 357-379.

Nassar, A. A. and Krawinkler, H. (1991). "Seismic Demands for SDOF and MDOF Systems", Report No. 95, The John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA.

Reinoso, E. and Ordaz, M. (1999). "Spectral Rations for Mexico City from Free-Field Recordings", Earthquake Spectra, Earthquake Engineering Research Institute, Vol. 15, No. 2, pp. 273-295, Oakland, CA.

Sociedad Mexicana de Ingeniería Sísmica, SMIS (2000). "Base Mexicana de Datos de Sismos Fuertes, Volumen II", Disco Compacto, México Distrito Federal.

Uang, C-M (1991). "Establishing R (or (Rw) and Cd Factors for Building Seismic Provisions", Journal of Structural Engineering, Vol. 117, No. 1, pp 19-28, American Society of Civil Engineers, New York, N. Y.

Varela, J. L, Tanner, J. E. and Klingner, R. (2006) "Development of Seismic Force-Reduction and Displacement Amplification Factors for Autoclaved Aerated Concrete Structures", Earthquake Spectra, Vol. 22, No. 1, pp. 267-286.