Overstrength factors for the seismic design of AAC structures

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SUMMARY
In this paper system overstrength factors (R) for AAC structures are evaluated. The R factors are calculated as the product of independent overstrength factors associated with the amount of flexural steel reinforcement, the actual yielding strength in this reinforcement, the rate of loading, the use of load and strength-reduction factors and the simplifications assumed in the design. These independent factors are evaluated for AAC wall structures designed in different soil types according to the current Mexico City Seismic Code (MCSC). Based on the results obtained in this work it is concluded that the obtained values of R for AAC structures are greater than those proposed in the MCSC. An equation is proposed to calculate R values for AAC structures as a function of the natural period of the structure and soil parameters.

Keywords: autoclaved aerated concrete, overstrength, wall-structures, seismic force-reduction factor

1. INTRODUCTION

The design of Autoclaved Aerated Concrete (AAC) structures in Mexico City is currently allowed only if these structures are designed using elastic forces. The main reason is that AAC structures are today not considered explicitly in the Mexico City Seismic Code (MCSC, 2004). For other structures as traditional concrete, steel or masonry structures, the mandatory appendix A of this seismic code prescribes that the design elastic seismic forces can be reduced by the product of a seismic force-reduction factor (Q´) and a system overstrength factor (R). The factor Q´ is a function of a ductility factor (Q) and the natural period of the structure (T). The factor R is a function of T and a characteristic period of the soil (T_a). A value of Q of 1.5 has been proposed for different AAC wall structures (Varela et al. 2007), but there is still the need to determine overstrength factors (R) to calculate values of Q´ for AAC wall structures.

Based on the literature review conducted in this work, it is concluded that the main sources of overstrength in structures are: 1) the actual amount and location of the flexural steel reinforcement, 2) the actual stress in this reinforcement, 3) the rate of loading during an earthquake, 4) the load and strength reduction factors used in the design, 5) the simplifications assumed in the design, 6) the redundancy in the structures, and 7) the presence of the non structural elements.

The overstrength associated with the flexural reinforcement depends mainly on the actual amount of steel reinforcement and its location within the element cross section (MacGregor, 1976). The actual amount of reinforcement is in general greater that that required in the design. This is related to the use of commercial steel bar diameters and the possibility that the minimum amount of steel reinforcement prescribed in codes controls the design. Changes in the location of the reinforcement can be associated with construction errors, among others. The overstrength related to the actual stress in the reinforcement is associated with the fact that fabricants produce steel with an actual yielding strength greater than that specified in codes. Another source of overstrength related to the stress in the reinforcement is the use of an elastoplastic stress-strain curve for design, neglecting strain hardening.

In Mexico, based on laboratory testing of bars with diameters smaller or equal to 13 mm, Rodriguez and Botero (1994) found that, in average, the actual yielding strength of the reinforcement is about 10% greater than that specified in design. In that work, different parameters are also specified to define the stress-strain curve of the steel reinforcement including strain hardening.

The yielding strength of the reinforcement depends also on the rate of load application during an earthquake. The rate of loading is related to the strain rate (ε_s), which is assumed static for values less or equal to 0.00001 1/s (Mander, 1984). That author proposed a relationship between the yielding strength for a given strain rate and the yielding strength for a static strain rate (D_s) (Eqn. 1.1). Mander (1984) concludes that Eqn. 1.1 can be use to modify not only the mechanical properties of the steel reinforcement but also the whole stress-strain curve.

$$D_s = 0.953\left(1+\left|\frac{\varepsilon_s}{700}\right|^{1/6}\right) \tag{1.1}$$

The axial compressive strength of concrete depends also on the rate of loading (Soroushian et al., 1986); however, changes in the compressive strength, such as 10%, do not result in important changes in the flexural capacity of a AAC wall.

The design of structural elements based on ultimate strength design is carried out using load factors (L_f) and strength-reduction factor (ϕ). These factors depend on the code used. For example, a value of ϕ of 0.9 is proposed for the flexural design of AAC walls (MSJC, 2011). The MCSC prescribes elastic design spectra for different soil types. During a severe earthquake, it is possible that the actual spectral acceleration, obtained from the corresponding response spectrum, would be different than that obtained from the design spectrum. In addition, the MCSC prescribes different methods to determine the design seismic forces. Those methods are the simplified, the static and the dynamics. In general, if any of the first two methods are used, the design seismic forces would be greater that those obtained from any of the dynamic methods.

The overstrength associated with the redundancy depends on the possible number and distribution of the plastic hinges in a structure. For the case of a cantilever wall, the redundancy can be neglected. The overstrength associated with the non structural elements depends on their distribution in the structure. In general it is difficult to quantify its strength and stiffness contribution.

In this work, system overstrength factors (R) are determined for AAC structures. The R factors are calculated as the product of independent overstrength factors. These independent factors are determined for AAC wall structures designed in different soil types according to the MCSC. The obtained values of R for AAC structures are compared with those proposed in the MCSC.

2. METHODOLOGY

The procedure used to determine the R factors is as follows: select AAC wall structures; different number of stories and wall lengths are considered. Design the AAC wall structures using the modal spectral analysis specified in the MCSC. Calculate independent overstrength factor for each of the AAC wall structures selected. Calculate system overstrength factors for the AAC wall structures.

2.1. Selection and design of AAC wall structures

The AAC structures selected were three-, four- and five-story cantilever-wall structures. The structures were selected as AAC wall structures because walls are the major structural elements resisting seismic forces. Typical wall dimensions of 3 m high and 0.25 m thick were used in every story of each structure. Wall lengths were assumed equal to 6.1 m, 5m, 4m and 3 m. Slabs were made of AAC planks 0.25 m thick. Live loads used were those specified in the Mexico City Loads Code

(MCLC, 2004). Density and compressive strength of AAC were those specified in ASTM C1452 for an AAC-6 material. Modulus of elasticity of AAC was that prescribed in MSJC (2011). A Poisson ratio of 0.2 was assumed (RILEM, 1993). Three soil types were considered: type I, type IIIa, and type IIIb (MCSC, 2004). A total of 36 AAC wall structures was analyzed, 12 for each soil type. The AAC structures were modeled as planar structures. A tributary width of 6.1 m was assumed to calculate the roof and story weights. **¡Error! No se encuentra el origen de la referencia.** shows the final story weights calculated for the selected structures. Details of the AAC structures and the weights calculations are presented in Bagundo (2005) and Chan (2007).

Table 2.1. Story and roof weights for AAC structures

Wall length (m)	Story weight (kN)	Roof weight (kN)
6.1	211.82	158.87
5.0	184.36	135.33
4.0	159.85	114.74
3.0	134.35	93.16

Bending moments and shear forces for the AAC wall structures were calculated using modal spectral analysis as specified in the MCSC. Elastic design spectrum for soil type I was reduced only by Q´as specified in Chapter 4. Elastic design spectra for soil types IIIa and IIIb were reduced by the product of Q´and R as specified in Appendix A. All modal spectral analyses were carried out using the computer program SAP2000 (Computers and Structures, Inc, 2007). Reduced properties were used for the AAC walls as proposed in Varela et al., 2006. Drift ratios of AAC wall structures were compared with a maximum value of 0.01 (Varela el al., 2006). In some structures in soil type I, the design base shear was smaller than that minimum specified in the MCSC. For those cases, an overstrength factor (R_{VMIN}) was calculated as the ratio between the minimum base shear and the reduced design base shear.

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2.2. Independent and system overstrength factors

Independent overstrength factors were calculated for each AAC wall structure. Sources considered were: the amount of flexural steel reinforcement, the actual yielding strength of the flexural steel reinforcement, the rate of loading during an earthquake, the load and strength reduction factors used in the design, and the simplifications assumed in the design. For the case of cantilever wall structures it was assumed that there is no overstrength associated with the redundancy. Overstrength related to non structural elements is neglected in this study. The system overstrength factors for the AAC structures were calculated as the product of the corresponding independent overstrength factors.

The amount of flexural reinforcement was selected for each AAC wall structure based on the overturning moments obtained from the modal analyses. Load and strength-reduction factors were assumed equal to one at this time. Steel reinforcement was selected using only 13 mm diameter corrugated bars with a specified yielding strength of 420 MPa. Bars were placed at 0.2 m from the wall ends. If additional flexural reinforcement was needed, it was placed at every 0.6 m as shown in Fig. 2.1. The overstrength factor associated with the amount of flexural steel reinforcement (R_{AS}) was calculated as the ratio between the actual amount of reinforcement and the design amount.

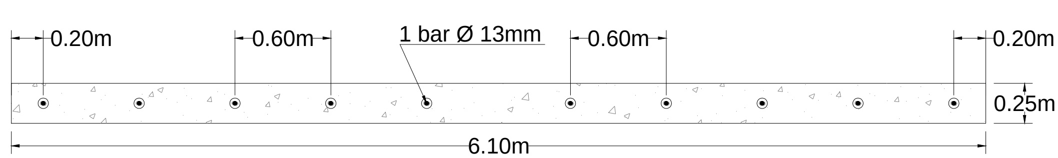

Figure 2.1. Distribution of flexural steel reinforcement in an AAC wall

The overstrength factor associated with the actual yielding strength of the flexural steel reinforcement (R_{FY}) was assumed constant and equal to 1.1 (Rodriguez and Botero, 1994). Increase in the steel strength associated with strain hardening was not considered because failure of AAC walls subjected to flexure is related to crushing of the compressive zone (Varela, 2003 and Tanner, 2003). The overstrength factor associated with the rate of loading (R_{VC}) was assumed equal to D_s as presented in Eqn. 1.1. Values of ε_s (Eqn. 2.1) were calculated dividing the maximum strain of AAC of 0.003 (MSJC, 2005) between the amount of time the structure needs to undergo that strain. This time was defined as the natural period (T) of the structure divided by four. The natural period was increased by a factor of 1.5 to consider that if AAC structures undergo inelastic deformations, the period increases.

$$\varepsilon_S = \frac{0.003}{1.5T/4} \qquad (2.1)$$

Overstrength factor associated with the use of load and strength-reduction factors (R_{FCR}) was calculated dividing the load factor of 1.1 (MCLC, 2004) by the strength reduction factor of 0.9 (MSJC, 2011). This factor was constant and equal to 1.22 for all AAC structures. Overstrength factors associated with simplifications in the design were calculated using suites of 10 earthquake ground motions representing the different soil types considered. Individual overstrength factors were calculated by dividing the spectral acceleration obtained from the response spectrum by that obtained from the corresponding design spectrum (Fig. 2.2). Average values were assumed as the final overstrength factor (R_{FD}). Response spectra for soil type I were scaled to represent in average the design forces. Response spectra for soils type IIIa y IIIb were not scaled because synthetic earthquakes used were developed to represent the spectral accelerations for period of 1 and 2 s, respectively (Fig. 2.2).

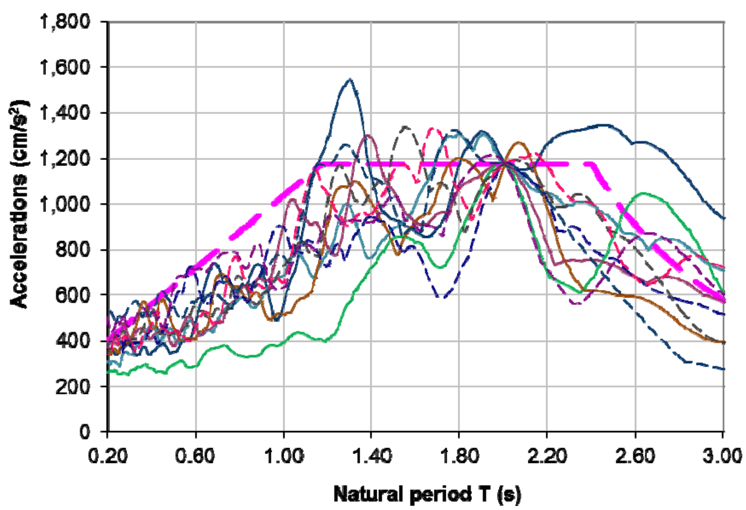

Figure 2.2. Response spectra and design spectrum for soil type IIIb

3. RESULTS

Table 3.1 shows the independent and system overstrength factors calculated for each AAC wall structure studied. Nomenclature "xx-yy-zz" used in column 1 of Table 3.1 is specified as follows: the first part represent the wall length, the second the number of stories and the last the soil type. The shaded rows presented in Table 3.1 represent cases were the drift ratios were greater than 0.01.

Table 3.1. Independent and system overstrength factors

Structure	T (s)	R_{MCSC}	Q'	R_{AS}	R_{FY}	R_{VC}	R_{FCR}	R_{FD}	R_{VMIN}	R
6M-3N-I	0.25	--	1.50	5.77	1.10	1.13	1.22	1.17	1.01	10.34
6M-3N-IIIA	0.25	2.13	1.24	3.64	1.10	1.13	1.22	1.88	-	10.40
6M-3N-IIIB	0.25	2.24	1.18	3.59	1.10	1.13	1.22	1.03	-	5.61
6M-4N-I	0.40	--	1.50	4.40	1.10	1.12	1.22	1.09	1.07	7.69
6M-4N-IIIA	0.40	2.05	1.38	2.21	1.10	1.12	1.22	2.15	-	7.13
6M-4N-IIIB	0.40	2.18	1.29	2.31	1.10	1.12	1.22	1.02	-	3.53
6M-5N-I	0.58	--	1.50	3.52	1.10	1.11	1.22	1.05	1.10	6.06
6M-5N-IIIA	0.58	2.00	1.50	1.52	1.10	1.11	1.22	2.13	-	4.82
6M-5N-IIIB	0.58	2.13	1.42	1.57	1.10	1.11	1.22	1.16	-	2.72
5M-3N-I	0.30	--	1.50	5.21	1.10	1.13	1.22	1.13	1.03	9.22
5M-3N-IIIA	0.30	2.10	1.28	3.03	1.10	1.13	1.22	2.05	-	9.41
5M-3N-IIIB	0.30	2.22	1.21	3.06	1.10	1.13	1.22	1.03	-	4.74
5M-4N-I	0.48	--	1.50	3.87	1.10	1.11	1.22	1.09	1.08	6.85
5M-4N-IIIA	0.48	2.02	1.46	1.76	1.10	1.11	1.22	2.12	-	5.58
5M-4N-IIIB	0.48	2.15	1.35	1.88	1.10	1.11	1.22	1.11	-	3.11
5M-5N-I	0.71	--	1.50	3.04	1.10	1.10	1.22	1.02	1.11	5.10
5M-5N-IIIA	0.71	2.00	1.50	1.32	1.10	1.10	1.22	1.64	-	3.20
5M-5N-IIIB	0.71	2.09	1.51	1.25	1.10	1.08	1.22	1.18	-	2.15
4M-3N-I	0.37	--	1.50	4.05	1.10	1.12	1.22	1.13	1.05	7.26
4M-3N-IIIA	0.37	2.07	1.35	2.12	1.10	1.12	1.22	2.07	-	6.62
4M-3N-IIIB	0.37	2.19	1.27	2.19	1.10	1.12	1.22	1.02	-	3.36
4M-4N-I	0.61	--	1.50	3.03	1.10	1.11	1.22	1.06	1.10	5.21
4M-4N-IIIA	0.61	2.00	1.50	1.31	1.10	1.11	1.22	2.06	-	4.00
4M-4N-IIIB	0.61	2.12	1.44	1.33	1.10	1.11	1.22	1.19	-	2.35
4M-5N-I	0.91	--	1.50	2.38	1.10	1.10	1.22	1.01	1.11	3.94
4M-5N-IIIA	0.91	2.00	1.50	1.03	1.10	1.10	1.22	1.20	-	1.82
4M-5N-IIIB	0.91	2.05	1.65	1.04	1.10	1.10	1.22	1.25	-	1.83
3M-3N-I	0.49	--	1.50	3.16	1.10	1.11	1.22	1.08	1.07	5.45
3M-3N-IIIA	0.49	2.01	1.47	1.42	1.10	1.11	1.22	2.07	-	4.39
3M-3N-IIIB	0.49	2.15	1.35	1.52	1.10	1.11	1.22	1.12	-	2.54
3M-4N-I	0.82	1.00	1.50	2.32	1.10	1.10	1.22	1.04	1.10	3.93
3M-4N-IIIA	0.82	2.00	1.50	1.01	1.10	1.10	1.22	1.46	-	2.17
3M-4N-IIIB	0.82	2.07	1.59	1.02	1.10	1.10	1.22	1.15	-	1.73
3M-5N-I	1.24	1.00	1.50	1.81	1.10	1.09	1.22	1.17	1.12	3.45
3M-5N-IIIA	1.24	2.00	1.50	1.02	1.10	1.09	1.22	1.37	-	2.01
3M-5N-IIIB	1.24	2.00	1.85	1.00	1.10	1.09	1.22	1.10	-	1.62

Fig. 3.1 shows the values of the system overstrength factors (R) as a function of the period T for the different soil types studied. In this figure, values of R, as specified in the MCSC, are also included for soil type IIIb. Values of R, as specified in the MCSC, for soil type IIIa are not included because are similar to those obtained for soil type IIIb.

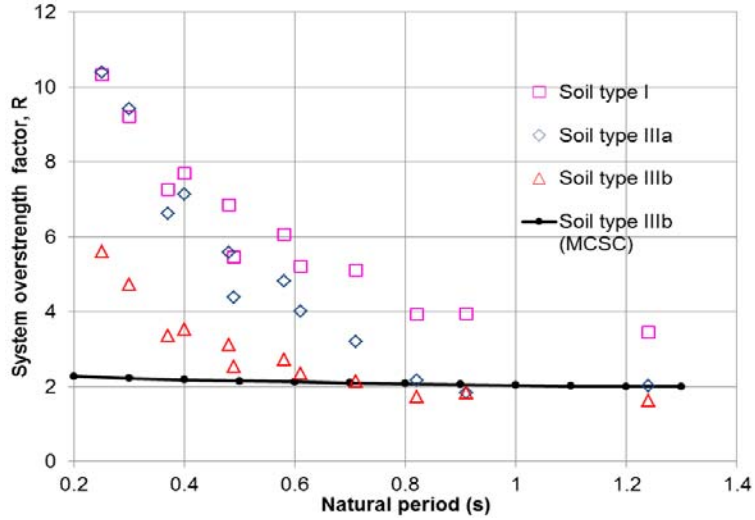

Figure 3.1. Values of R for AAC structures as a function of the period

Eqn. 3.1 was developed for the different values of R as a function of the period (T) and the soil parameters α and β. For soil type I $\alpha = 0.334$ and $\beta = -0.072$, for soil type IIIa, $\alpha = 0.945$ y $\beta = -0.436$, and for soil type IIIb, $\alpha = 0.840$ and $\beta = -0.237$. Eqn. 3.1 was obtained using the least squares method.

$$R = \frac{1}{\alpha\sqrt{T} + \beta} \tag{3.1}$$

Fig. 3.2 compares the values of R for AAC structures from Table 3.1 and those obtained from Eqn. 3.1.

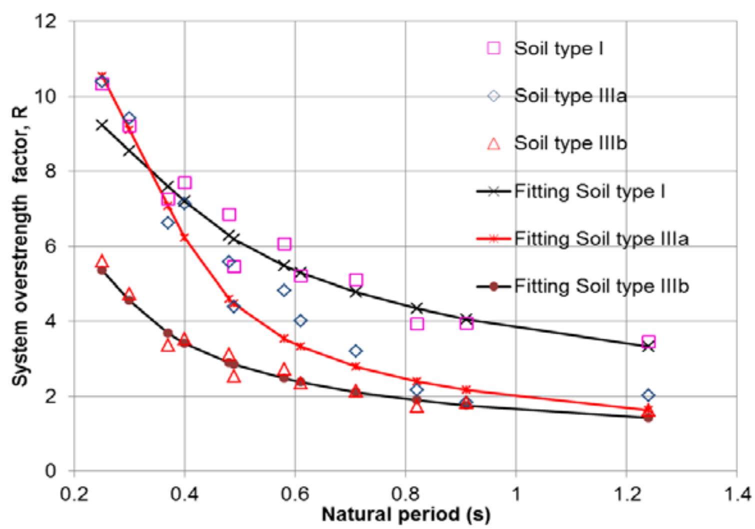

Figure 3.2. Values of R for AAC structures

4. DISCUSSION

Table 3.1 shows that the factors R_{FY} y R_{FCR} do not depend on T, and that R_{VC} is not sensitive to changes in this variable. This shows that the factor R depends mainly on the factors R_{AS}, R_{FD} and R_{VMIN}. Fig. 3.2 shows that the factor R decreases as T increases. This decrement is associated with the factor R_{AS} which varies from 1.01 to 5.77 (Table 3.1). The increment in the value of T can be related to both an increment on the number of stories or a decrement in the wall length. In the first case as the number of stories increases, the overturning moment increases and therefore a larger amount of flexural reinforcement is needed. In the second case, as the wall length is reduced, a larger amount of steel reinforcement is also required.

Fig. 3.1 shows that, the values of R for soil type I are smaller than those corresponding for soil types IIIa or IIIb. At the same time, the values of R for soil type IIIa are smaller than those corresponding to soil type IIIb. These differences are associated with magnitude of the spectral accelerations and the shape of the response spectra. For soil type, the values of T for the structures studied are located in the zone of maximum accelerations; for soil types IIIa and IIIb the values of T for the structures studied are not located in the zone of maximum accelerations.

The values of R obtained for the AAC structures are in general greater than those specified in the MCSC for soil types IIIa and IIIb. In some particular cases, for large periods, the values of R obtained for AAC structures were smaller than those proposed in the MCSC. These cases correspond to structures were drift ratio criterion was not satisfied. For the case of soil type I, the MCSC does not prescribed values as those obtained in this work.

5. CONCLUSIONS

Based on the results obtained in this work using AAC cantilever wall structures, the following conclusions are presented: the system overstrength factor depends mainly on the factors R_{AS}, R_{FD} and R_{VMIN}. The system overstrength factor decreases as the natural period of the structure increases. The system overstrength factors for soil type I are smaller than those obtained for soil type IIIa. At the same time, the system overstrength factors obtained for soil type IIIa are smaller than those obtained for soil type IIIb. The system overstrength factors are greater than those specified in the MCSC in soil types IIIa and IIIb. An equation is proposed to determine the system overstrength factor as a function of the natural period of the structure and the soil parameters.

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