Engineering Structures 93 (2015) 61–69

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Effect of lightweight and low-strength concrete on seismic performance of thin lightly-reinforced shear walls

Julian Carrillo [a,*], Juan M. Lizarazo [b], Ricardo Bonett [c]

[a] Departamento de Ingeniería Civil, Universidad Militar Nueva Granada, UMNG, Cra. 11, No. 101-80, Bogotá, Colombia
[b] Departamento de Ingeniería Civil, Universidad Nacional de Colombia, Bogotá, Colombia
[c] Departamento de Ingeniería Civil, Universidad de Medellín, Colombia

ARTICLE INFO

Article history:
Received 20 November 2014
Revised 13 February 2015
Accepted 9 March 2015
Available online 25 March 2015

Keywords:
Shear walls
Thin walls
Energy dissipated
Stiffness degradation
Low-rise housing
Shake table tests
Lightweight concrete
Low-strength
Lightly-reinforced
Welded-wire mesh

ABSTRACT

Although several research programs have investigated the performance of structural elements made of lightweight concrete, there is a limited understanding of the behavior of lightweight shear walls under seismic conditions. In this paper is summarized an experimental study that comprised quasi-static cyclic tests and shake table tests of twenty walls, conducted to provide information on the effect of lightweight and low-strength concrete on seismic performance of thin lightly-reinforced shear walls. Test results indicate that shear strength, drift ratios and energy dissipated at different limit states of lightweight concrete walls were larger in comparison to walls made of normalweight concrete. Measured performance also indicate that the reduction factor proposed by ACI 318-11 and NTC-C does not capture adequately the influence of lightweight and low-strength concrete. Thus, shear strength of thin lightly-reinforced, lightweight concrete shear walls can be calculated without any modification factor.

1. Introduction

The shear strength of concrete walls, and the new materials and construction techniques have positioned the industrialized concrete housing as a proficient option for providing safety under seismic events, for stimulating environmental conservation and for promoting the reduction of cost of construction, operation and maintenance. To build one- or two-story concrete wall structures in several Latin American countries, housing designers frequently use thin walls (100-mm thick), normalweight and lightweight concrete having compressive strengths of 15–20 MPa, web shear reinforcement close to that prescribed by the American Concrete Institute's building code (ACI 318-11) [1], and web shear reinforcement made of welded-wire meshes. Lightweight concrete provides thermal properties to houses and promotes energy savings, suitable acoustic and fire-resistance, and the reduction of dead loads and the consequent reduction of the seismic base shear. All these features are a consequence of attaining speed of construction and economy in a very competitive housing market.

Most current building codes implicitly point out that the use of lightweight concrete in members experiencing high levels of inelastic deformation in large earthquakes can show some problems related to shear failures due to the potentially brittle nature of the material [2]. The brittle nature of shear failures is classified as a mode of deformation that should be avoided in designing of structures. Although several experimental programs have studied the performance of lightweight concrete members [2–7], the effect of lightweight concrete has been investigated mainly with concretes having a nominal compressive strength higher than 20 MPa. In addition, the experimental evidence on the seismic performance of low-rise housing having lightweight and low-strength concrete shear walls is limited or non-existing.

There is currently a major necessity for including reliable provisions for design of lightweight concrete in building codes. Taking into account that ACI 318-11 [1] requirements of lightweight concrete were based principally on beams and slabs test, it was considered desirable to supplement this information with testing of lightweight and low-strength concrete shear walls. This experimental study was conducted to provide information on the effect of lightweight and low-strength concrete on seismic performance of thin lightly-reinforced shear walls, and to contribute to the

* Corresponding author. Tel.: +57 1 6500000x1705; fax: +57 1 6370557.
E-mail address: wjcarrillo@gmail.com (J. Carrillo).

http://dx.doi.org/10.1016/j.engstruct.2015.03.022
0141-0296/

development of codes like the ACI 318-11 [1] and Mexico City's Buildings Standards for Design and Construction of Concrete Structures NTC-C-04 [8]. The experimental program comprised quasi-static cyclic tests and shake table tests of ten lightweight and low-strength concrete shear walls to explore the performance associated to different limit states as compared to similar walls made with normalweight concrete. The main objective of this research was to quantify any reduction or increase in shear strength, displacement, stiffness and energy dissipated of the lightweight concrete walls when compared to normalweight concrete walls. The effect of the concrete type was evaluated using the wall properties obtained from current design and construction practice found in typical low-rise housing in several Latin American countries such as aspect ratio, web steel reinforcement ratio, type of web shear reinforcement, and type of testing.

2. Modification factors for lightweight concrete

The ACI Committee 213, Lightweight aggregate and concrete, was organized in 1946. During the 50's, the structural lightweight-aggregate concrete became extensively used and recommendations for structural design, including methods for consideration of shear in beam and frames, were developed under the guidance of Committee 213. However, the shear strength of slabs and walls was not considered [3]. Shear requirements for structural lightweight concrete slabs different from those specified for normalweight concrete were first developed on the basis of a limited testing program carried out by Hognestad et al. [3], for inclusion in ACI 318-63 [4].

In the past, properties of lightweight concrete have been compared with those of normalweight concrete, and usually the reference standard has been a single normalweight material. With several million cubic meters of lightweight concrete being placed each year, such a comparison of properties may no longer be appropriate. The data on various structural properties are presented as reasonable conservative values to be expected in relationship to some fixed properties such as compressive strength or density [9].

It is widely known that the strength of concrete to diagonal tension stress is related to tensile properties rather than compressive strength. Nevertheless, since only compressive strength is usually specified and controlled in concrete construction of structures, shear and diagonal tension resistance have traditionally been related in design to compressive strength f'_c. Most codes recommended that shear strength be expressed in terms of the square root of compressive strength, $(f'_c)^{1/2}$ [3]. The ACI 318-11 [1] and NTC-C-04 [8] building codes include the following specific recommendations for the structural lightweight concrete.

2.1. ACI 318-11 building code

According to ACI 318-11 building code [1], lightweight concrete contains lightweight aggregate and an equilibrium density between 1140 and 1840 kg/m^3. In accordance with section 8.6 of ACI 318-11 building code, to account for the use of lightweight concrete, unless specifically noted otherwise, a modification factor λ appears as a multiplier of $(f'_c)^{1/2}$ in all applicable equations and sections of the code. Factor λ intends to reflect the lower tensile strength of lightweight concrete, which can reduce shear strength, friction properties, splitting resistance, bond between concrete and reinforcement, and can increase development length compared with normal weight concrete of the same compressive strength. Two alternative modification procedures are provided in ACI 318-11 building code [1] to determine λ. The first alternative is based on the assumption that the tensile strength of lightweight concrete is a fixed fraction of the tensile strength of normalweight concrete. The multipliers are based on data from tests on many types of structural lightweight concrete. For instance, $\lambda = 0.85$ for sand-lightweight concrete and 0.75 for all-lightweight concrete. Linear interpolation between 0.75 and 0.85 is permitted, on the basis of volumetric fractions, when a portion of the lightweight fine aggregate is replaced with normal weight fine aggregate. Linear interpolation between 0.85 and 1.0 is also permitted, on the basis of volumetric fractions, for concrete containing normal-weight fine aggregate and blend of lightweight and normal-weight coarse aggregates. For normal-weight concrete, $\lambda = 1.0$.

The second alternative is based on laboratory tests to determine the relationship between average splitting tensile strength, f_t, and the specified compressive strength f'_c, for the lightweight concrete being used. For a lightweight aggregate from a given source, it is intended that appropriate values of f_t be obtained in advance of design. If average splitting tensile strength of lightweight concrete, f_t, is specified, λ is calculated using Eq. (1). For normal-weight concrete, the average splitting tensile strength, f_t, is approximately equal to 0.56 $(f'_c)^{1/2}$ [5,6].

$$\lambda = \frac{f_t}{0.56\sqrt{f'_c}} \leqslant 1.0 \quad \text{(MPa)} \tag{1}$$

For earthquake-resistant structures, section 21.1.4.3 of ACI 318-11 [1] states that specified compressive strength of lightweight concrete, f'_c, should not exceed 34.5 MPa unless it is demonstrated by convinced experimental evidence that structural members made with lightweight concrete provide strength and toughness equal to or exceeding those of comparable members made with normal weight concrete of the same strength. According to section 18.2.5.1 of ACI 318-14 draft building code, this limitation is specified primarily because of paucity of experimental and field data on the behavior of members made with lightweight concrete subjected to displacement reversals in the nonlinear range. If convincing evidence is developed for a specified application, the limit on maximum specified compressive strength of lightweight concrete may be increased to a level justified by the evidence.

2.2. NTC-C Mexico City Building Standards

The Mexico City's Buildings Standards for Design and Construction of Concrete Structures NTC-C-04 [8], define the lightweight concrete having a density of fresh concrete (unit weight) lower than 1930 kg/m^3. Although NTC-C-04 does not state explicitly the factor λ, according to the requirements specified in section 12.1 of NTC-C-04, factor λ is equivalent to that defined in Eq. (2).

$$\lambda = \frac{f_t}{0.63\sqrt{f'_c}} \leqslant 1.0 \quad \text{(MPa)} \tag{2}$$

In addition, NTC-C-04 states that the strain of lightweight concrete at failure should be computed as $0.003 \times E_{cn}/E_{cl}$, where E_{cn} and E_{cl} are the modulus of elasticity of normalweight and lightweight concrete having the same compressive strength, respectively.

3. Experimental program

Twenty concrete walls were tested to provide information on shear strength and displacement capacity of structural lightweight aggregate concrete, and to evaluate shear requirements specified by ACI 318-11 [1] and NTC-C [8] building codes. The testing program consisted of both lightweight and normalweight concrete specimens such that a direct comparison could be made. The effect of the concrete density (normalweight versus lightweight) was evaluated jointly with the most representative wall properties in