Engineering Structures 73 (2014) 39–53

Contents lists available at ScienceDirect

Engineering Structures

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

Behaviour of RC buildings with large lightly reinforced walls along the perimeter

Marisa Pecce [1], Francesca Ceroni *,[1], Fabio A. Bibbò [1], Alessandra De Angelis [1]

Engineering Department, University of Sannio, Benevento, Italy

A R T I C L E I N F O

Article history:
Received 21 September 2013
Revised 8 March 2014
Accepted 23 April 2014
Available online 22 May 2014

Keywords:
Large lightly reinforced walls
Seismic performances
Dynamic behaviour
Nonlinear analysis
Ductility
Over-strength

A B S T R A C T

Reinforced Concrete (RC) walls are defined as large lightly reinforced walls if they are not provided of high reinforcement percentage or if they are lack of reinforcement details usually required to improve the ductility of the structure. This type of walls gained relevance in 1950s–1970s constructions because of their good performances under seismic actions. Real earthquakes have, indeed, demonstrated that buildings constructed with large lightly reinforced walls, characterised by adequate area respect to the floor extension, could suffer lower damages in comparison with traditional RC framed buildings. Moreover, a widespread use of such a construction typology is outstanding thanks to the diffusion on the market of new types of integrated formworks, including insulating materials such as polystyrene, that are being used for casting concrete and are aimed to obtain a higher energetic efficiency and build structures made of continuous lightly reinforced walls. Nevertheless, there is a lack of both experimental information and specific design indications in technical codes on this type of construction.

This paper firstly reviews the European code requirements for large lightly reinforced walls. Then, some experimental tests on RC walls in the existing literature are studied in detail also by means of a nonlinear Finite Element (FE) model.

Finally, the performances of a whole RC building designed with both large lightly reinforced walls along the perimeter and internal frames have been also exploited by linear dynamic and static nonlinear analysis. The analysis are mainly aimed to highlight the influence of in-plane stiffness of the floor on the dynamic behaviour of the structure and to assess the contribution of both ductility and over-strength to the behaviour factor, i.e. to the seismic performance of such type of buildings, considering the lack of information in the technical literature about these features.

1. Introduction

Structural Reinforced Concrete (RC) walls are an efficient system for buildings that must withstand significant seismic actions, particularly because they allow limiting displacements in tall buildings. In recent decades, buildings with large lightly reinforced walls have been constructed in countries such as Kyrgyzstan, Canada, Romania, Turkey, Colombia and Chile [1]. Recent analyses of the performances of some of these buildings after the earthquake occurred in Chile in 1985 [2,3] have demonstrated a lower damage level in comparison with RC framed buildings, if the walls' area is adequate respect to the floor extension, as it will be discussed more in detail afterwards.

Buildings having both structural walls located along the perimeter and inner RC frames also fall in the category of RC buildings made with large lightly reinforced walls; this particular distribution not only gives to the building high resistance and stiffness to the lateral actions but also provides an increased flexibility within the organisation of the internal spaces. This is possible thanks to the presence of RC frames made of columns characterised by small sections that have to support only the vertical loads.

Many examples of such type of building were built during the 1950s through the 1970s; in particular, some of the most relevant to be cited are: the Santa Monica Hospital in California that was damaged by the Northridge earthquake of 1994, the St. Joseph's Healthcare Orange and the St. Jude Medical Center that have been studied in detail especially for what concerned the behaviour of their outer walls [4–6].

Currently, the use of large lightly reinforced walls located along the perimeter of the building is being rediscovered both to improve the thermal insulation performance and reduce the construction

* Corresponding author. Tel.: +39 0824305575; fax: +39 0824325246.
E-mail addresses: pecce@unisannio.it (M. Pecce), ceroni@unisannio.it (F. Ceroni), fabiobibbo@libero.it (F.A. Bibbò), dea.alessandra@gmail.com (A. De Angelis).
[1] Tel.: +39 0824305575; fax: 39 0824325246.

http://dx.doi.org/10.1016/j.engstruct.2014.04.038
0141-0296/

Nomenclature

A_c	effective area of concrete in tension
$A_g{\cdot}f'_c$	compressive strength of the concrete section
f_1	tensile stress
f_{cm}	compressive strength of the concrete
f_{cd}	design compressive strength of the concrete
f_y	yielding strength of the steel
f_{cr}	tensile strength of the concrete
F_y	yielding strength of the SDOF system
G	shear stiffness of the concrete
h_w	total height of the wall
H	height of the structure
K	stiffness of the system
K_C	stiffness of the columns
k^*	stiffness of the SDOF system
L_{wi}	length of the *i*th wall
m^*	mass of the SDOF system
PGA	peak ground acceleration
q	behaviour factor
R_μ	ductility factor of the structure
R_s	over-strength factor of the structure
R_ξ	redundancy factor of the structure
S	stiffness of the columns
S_{ref}	reference stiffness of the columns
T_1	fundamental period of vibration
T^*	the period of vibration of the SDOF system
T_C	the start period of the spectrum with constant velocity
V	shear at the base of the building
V^*	shear at the base of the SDOF system
V_{col}	total shear of the columns
V_{wall}	total shear of the walls
ρ_1	wall area/floor area ratio
β	reduction factor of shear stiffness G
γ	shear strain
Γ	participating factor
δ	displacement at the top of the building
δ^*	displacement at the top of the SDOF system
ε_1	tensile strain
τ	shear stress
ρ_s	reinforcement percentage

time. These goals are being realised in systems consisting of formworks made of insulating materials or by 'sandwiching' the insulation material between two layers of concrete [7,8]. The use of these innovative and sustainable technologies improve the overall thermal resistance of the building and allow the construction of the walls. Furthermore, similar techniques are also utilised for realising RC floors in which the bricks are made of insulating materials (such as expanded polystyrene (EPS)) that do not contribute to the plane stiffness of the floor. In fact the maximum elastic modulus of the usual bricks is bit lower than the one of concrete, i.e. about 25,000 MPa, while the modulus along the orthogonal direction is about the half of the maximum one. Conversely, the EPS bricks have a negligible elastic modulus with respect to concrete and, thus, the plane stiffness of the floor can be assumed as the same of the solid concrete slab.

In this paper, firstly the characteristics of large lightly reinforced walls are surveyed to emphasise their differences from the so-called 'ductile walls' in terms of mechanical behaviour and requirements furnished by both Italian [9] and European codes [10] for seismic design. In particular, ductile walls require more expensive reinforcement percentages and construction details.

The technical literature has been then examined in order to highlight the behaviour of RC buildings made with large lightly reinforced walls under seismic actions [3,11,12].

The nonlinear behaviour of two large lightly reinforced walls experimentally tested has been also assessed by means of two numerical Finite Element (FE) models developed by using the SAP2000 [13] and DIANA 9.4 [14] software. These analyses were aimed to set constitutive relationships of materials, type of finite elements and smeared cracking model to be introduced in the FE model in order to achieve the best fitting with some experimental results. In particular, two smeared cracking (fixed or rotating) models have been considered and the parameter β defined as "shear retention factor" in the fixed cracked model has been varied to examine its effect on the nonlinear behaviour of the wall.

Finally, a case study representing a RC building with lightly reinforced walls along the perimeter has been addressed in a FE model by adopting the same approach used in the numerical analyses carried out on the single walls. Some features have been investigated for this type of building that are still lack in the technical literature. Linear dynamic analysis have been developed in order to define the influence of the in-plane stiffness of the floor, that is usually assumed rigid without any verification, on the dynamic behaviour of the whole structure. To this aim also a comparison with a traditional framed RC building has been carried out. The influence of the floor stiffness is analysed both in terms of dynamic behaviour (vibration period and participating mass) and shear force distribution among the walls and the columns. Such an effect is examined also in order to evaluate the role of innovative light floor systems, which cannot be considered as rigid in their plane, in RC buildings made with large lightly walls.

Furthermore, nonlinear static analysis has been also attended in order to evaluate for the case study the contribution of ductility and over-strength to the behaviour factor, q, i.e. to the seismic performances.

2. Lightly reinforced walls

2.1. Code indications for design

Large lightly reinforced walls are defined by Eurocode 8 [10] based on various geometric requirements and on their dynamic behaviour, as follows:

> "A wall system shall be classified as large lightly reinforced walls system, if, in the horizontal direction of interest, it comprises at least two walls with a horizontal dimension of not less than 4.0 m or $2/3h_w$, whichever is less, which collectively support at least 20% of the total gravity load from above in the seismic design situation, and has a fundamental period T_1, for assumed fixity at the base against rotation, less than or equal to 0.5 s. It is sufficient to have only one wall meeting the above conditions in one of the two directions, provided that: (a) the basic value of the behaviour factor, q_0, in that direction is divided by a factor of 1.5 over the value given in Table 5.1 and (b) that there are at least two walls meeting the above conditions in the orthogonal direction".

In addition, a note in the same code clarifies that, for this type of wall, the seismic energy is transformed into potential energy (through a temporary lifting of the structural mass) and that this energy is dissipated through the rocking of the walls.

For these walls, the formation and rotation of plastic hinges do not occur due to their large dimensions and to the absence of a