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Seismic performance of HSC dual systems irregular in elevation

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Abstract This paper presents a study on the seismic nonlinear performance of 86 multistory dual systems irregular in elevation and constructed from normal strength concrete (with f_c = 25 MPa) and high-strength concrete (with f_c = 75 MPa). The applicability of the Static Equivalent Lateral Force (SELF) method used by the seismic codes in Europe (Eurocode 8), in the United States (IBC-2012) and in Egypt (EC201-2008) when applied to dual systems irregular in elevation and constructed from NSC and HSC is examined. In addition, the reliability of the criteria provided by the studied codes, in order to separate the regular from irregular dual systems is also verified. Records of two real earthquakes (El Centro and Parkfield) and one artificial earthquake, with wide ranges of frequency content have been selected as input ground motions. The results showed that the limits in IBC-2012 and EC201-2008 aimed to identify the lateral stiffness irregularity are satisfactory and can be relaxed by about 10%.

1. Introduction

Recently, the use of high-strength concrete (HSC) has become attractive in tall buildings as well as in earthquake-resistant structures [1]. On the one hand, for architectural reasons, many multistory buildings are designed with horizontal stiffness changes, change in mass storey, and for reasons or restrictions imposed by local laws, many multistory buildings are designed with setbacks. Using HSC in tall dual systems leads to smaller size of the reinforced concrete walls and columns in the lower stories. This is associated with a change in the lateral resistance of these structures when subjected to ground motions. Most of the available studies [2–8] are meant to the seismic behaviour of reinforced concrete building frames with irregularity in elevation and constructed from Normal Strength Concrete 'NSC'. On the other hand, the use of the approximate Static Equivalent Lateral Force 'SELF' method to estimate the forces developed in buildings during an earthquake is still recommended by many current codes such as the

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International Building Code 'IBC-2012' [9], the Eurocode 8 'EC-8' [10] and the draft of the Egyptian Code for Loads 'EC201-2008' [11]. The SELF method is based on a number of assumptions which are true for regular structures. However, the definition of irregular structures for different vertical irregularities; stiffness, mass and setbacks differ among these codes.

The main objective of this paper is to study the seismic nonlinear performance of multistory dual system buildings constructed from NSC and HSC up to 75 MPa and irregular in elevation. The applicability of the SELF methods in IBC-2012, EC-8 and EC201-2008 when applied to dual system buildings with different vertical irregularities is evaluated. The reliability of the criteria provided by the codes considered in this study, to separate the regular from irregular dual system buildings, is also verified.

2. Seismic codes provisions for vertical irregularities

2.1. IBC-2012

Building irregularity is based on the following:

- A soft storey is one in which the lateral stiffness is less than 70% of that in the storey above, or less than 80% of the average stiffness of the three stories above.
- Mass irregularity shall be considered to exist where the effective mass of any storey is more than 150% of the effective mass of an adjacent storey. A roof that is lighter than the roof below need not be considered.
- Vertical geometric irregularity shall be considered to exist where the horizontal dimension of the lateral force-resisting system in any storey is more than 130% of that in adjacent storey. One-storey penthouses need not be considered.

2.2. EC-8

According to the EC-8, a building can be considered regular if:

- Both the lateral stiffness and the mass of the individual stories remain constant or are reduced gradually, without abrupt changes, from the base to the top.
- For gradual setbacks preserving axial symmetry, the setback at any floor is not greater than 20% of the previous plan dimension in the direction of the setback. For a single setback within the lower 15% of the total height of the main structural system, the setback is not greater than 50% of the previous plan dimension. If the setbacks do not preserve symmetry, in each face the sum of the setbacks at all stories is not greater than 30% of the plan dimension at the first storey, and the individual setbacks are not greater than 10% of the previous plan dimension.

2.3. EC201-2008

The regularity requirements of EC201-2008 are similar to that in EC-8 except:

- Stiffness irregularity shall be considered to exist where the lateral stiffness is less than 75% of that in the storey above.
- Mass irregularity shall be considered to exist where the effective mass of any storey is more than 150% of the effective mass of an adjacent storey.

3. Nonlinear analysis

3.1. Analytical modelling

The seismic analysis in this study has been performed using the inelastic computer program IDARC-2D 'Version 6.1' [12] which contains many nonlinear structural elements. The structure is modelled as a 2D assemblage of nonlinear elements connected by a number of finite deformable elements, or members. Beams and columns are modelled as inelastic single component elements with distributed flexibility. The P-Δ effect is accounted for. The damping coefficients are assumed as 5% of the critical damping in the first two vibrational modes. The building is subjected to a horizontal base acceleration in the plane of the building. The differential equation of motion is formulated in an incremental form and integrated using a small time interval. The basic model of IDARC-2D uses three primary parameters and some secondary related parameters to characterize stiffness degradation, strength deterioration and pinching during load reversals.

3.2. Adopted material models and properties

The model suggested by Daniel and Patrick [13] for NSC and HSC in compression has been adopted. This model takes into account the effect of confinement on the concrete strength. The value of the strain at maximum strength of unconfined concrete is assumed equal to 0.002 and the value of the strain for half of the maximum strength of unconfined concrete is equal to 0.004. The modulus of elasticity for NSC and HSC is obtained from the equation recommended by the ACI 318 code [1]. For concrete in tension, the model used by Massicotte et al. [14] is adopted. For the steel reinforcement bars, a trilinear stress–strain relationship is adopted. The modulus of elasticity of the steel bars is taken equal to 200 kN/mm^2. The adopted model for pullout of the steel bars is that suggested by Fillippou et al. [15].

4. Selection of earthquake ground motions

Four earthquake records (EL Centro, Parkfield, San Fernando and New Mexico earthquakes) were analysed in this study in order to cover a wide range of earthquake frequency content. The acceleration response spectra for each of the four earthquake records have been generated and the acceleration time histories of El Centro and Parkfield earthquake records, Fig. 1, were chosen for the analysis in this study.

These two earthquake records match the 'highest design level' earthquakes in the United States according to the IBC-2012 and Europe according to the EC-8 (for high ductility structures or ductility class high). The computer program SIMQKE [16] was used for generating many artificial acceleration time histories; from these the profile shown in Fig. 2a was chosen to represent the 'probable design level' earthquakes for the highest design level in Egypt according to the EC201-2008