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Design recommendations for achieving "strong column-weak beam" in RC frames

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ABSTRACT

This paper deals with the realization of ductile failure of RC frames with cast in-situ slabs. The cyclic loading experiments of two spatial reinforced concrete (RC) frames, a control specimen and a RC frame with cast in-situ slabs, are carried out. The failure pattern and the role of slabs are experimentally studied. Tests results indicate that slabs can change the failure pattern of RC frames from a typical "strong-column-weak-beam" failure to the "strong-beam-weak-column" failure. The slab reinforcement enhances the resistance moment of the beams, which is the main reason to form "strong-beam-weak-column". The parameters such as axial compression ratio, thickness of slab, concrete strength, reinforcement ratio of slab and stiffness of transverse beam are investigated by Finite Element Analysis (FEA). Strut and tie model of slab is proposed to calculate the effective slab width. Simple equations are derived by a 95% guarantee rate based on 200 models. The required ratio of column-to-beam strength is studied based on the tests and FEA data. A reasonable required ratio is proposed to avoid the brittle failure of the RC frames for seismic design.

1. Introduction

Reinforced Concrete (RC) frames are the most popular structural system for multistory buildings in many parts of the world. However, these buildings have shown poor performance during strong earthquakes in last few decades. For example, on October 8, 2005 an earthquake of 7.6 (Mw) struck the Kashmir of Pakistan, where the main damages of RC frames were the beam-column failure and the story failure (Fig. 1) [1]. Another earthquake of 6.2 (Mw) struck the Abbruzzo region of Italy on April 6, 2009. Seismic damage investigation showed that columns seem to have failed in compression before the yielding of beams (Fig. 2) [2]. Wenchuan China suffered a magnitude 8.0 earthquake on 12 May 2008. The main failure of RC frames was caused by "strong beam-weak column" (Fig. 3) [3,4]. Marmara earthquake of August 17, 1999 and Van earthquake on October 23, 2011 in Turkey showed that the slab affection was one of the reason why RC frames were damaged (Fig. 4) [5]. The similar failure modes were observed in the magnitude 6.6 earthquake in Bam on December 26, 2003 in Iran (Fig. 5) [6]; and in the magnitude of 7.6 earthquake in Chi-Chi Taiwan in 1999. According to reference [7], the "strong column-weak beam" concept was not implemented in the design of those school buildings. Thus, plastic hinges appeared in columns earlier than in beams (Fig. 6) [7]. The failure of those RC frames was against the ductility design concept of the existing Code [8–11]. Can the concept of "strong column-weak beam" be realized according to the existing Codes?

Based on the existing design codes, it is required that the total column moment strength be larger than the total beam moment strength at a joint in order to guarantee that beams yield before columns do in strong earthquakes, as shown below:

(1) ACI 318-14 [8]

$$\sum M_{nc} \geqslant \frac{6}{5}\sum M_{nb} \tag{1}$$

where $\sum M_{nc}$ = sum of nominal flexural strengths of columns framing into the joint, evaluated at the faces of the joint; $\sum M_{nb}$ = sum of nominal flexural strengths of the beams framing into the joint, evaluated at the faces of the joint. Where the slab is in tension under

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Fig. 1. Story failure of RC frame (Kashmir).

Fig. 2. Collapse of hotel (Italy).

Fig. 3. Column damage (Wenchuan).

moments at the face of the joint, slab reinforcement within an effective slab width as defined in article 8.12 and 8.13 shall be assumed to contribute to $\sum M_{nb}$ if the slab reinforcement is developed at the critical section for flexure.

Fig. 4. Strong beam weak column failure (Turkey).

Fig. 5. The plastic hinge in a weak column (Iran).

Fig. 6. Collapse of school (Taiwan).

(2) EC 8 [9]

The following condition should be satisfied at all joints of primary or secondary seismic beams with primary seismic columns:

$$\sum M_{Rc} \geqslant 1.3 \sum M_{Rb} \tag{2}$$