Engineering Structures 32 (2010) 2394–2406

Contents lists available at ScienceDirect

Engineering Structures

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

Assessment of RC moment frame buildings in moderate seismic zones: Evaluation of Egyptian seismic code implications and system configuration effects

S.S.F. Mehanny [a,*], H.A. El Howary [b]

[a] *Structural Engineering Department, Cairo University, Egypt*
[b] *Structural Engineer, DAR Al-Handasah, Cairo, Egypt*

ARTICLE INFO

Article history:
Received 4 November 2009
Received in revised form
21 February 2010
Accepted 4 April 2010
Available online 7 May 2010

Keywords:
RC moment frames
Ductile
Moderate seismic zones
Codes
Response modification factors

ABSTRACT

Building code restrictive seismic design provisions and building systems type and configuration have remarkable implications on seismic performance of reinforced concrete moment framed structures. Seismic assessment of ductile versions of low- to mid-rise moment frames located in moderate seismic zones is carried out through comparative trial designs of two (4- and 8-story) buildings adopting both space and perimeter framed approaches. Code-compliant designs, as well as a proposed modified code design relaxing design drift demands for the investigated buildings, are examined to test their effectiveness and reliability. Fragility curves for the frames are generated corresponding to various code-specified performance levels. Code preset lower or upper bounds on either design acceleration or drift, respectively, that would control the final design are also addressed along with their implications, if imposed, on the frames' seismic performance. The trial design study demonstrates that built-in static overstrength is generally larger for space frames than for perimeter frames, whereas the force reduction attributable to inelastic dynamic response differs from one frame type to the other for various investigated heights and for different target performance levels. Nonetheless, all trial designs are shown to meet the minimum performance implied by building code provisions but with varying margins. However, the study suggests that more consistent reliability for designed structures can be achieved by disaggregating the force reduction factor into its static and dynamic parts and that code default values of this factor for some building types would be better reduced for a more reliable performance.

1. Introduction

Performance-Based Design (PBD) is now widely recognized as the pre-eminent seismic design methodology for structures. The advent of PBD methodologies now requires that engineers develop code-compliant structures that also achieve specific performance objectives. Accordingly, it is necessary to develop efficient designs with predictable seismic response. To this day, the seismic designs of most general and some complex building structures are performed with Force-Based Design (FBD) method. This method is conceptually straightforward and thus appealing, but relies heavily upon unique, semi-empirical, force reduction factors and displacement equivalences for a selected lateral force resisting structural system. These factors are largely based on consensus opinion of code committees. The FBD methodology may yield life-safe designs in most cases; however, its ability to deliver designs that achieve specific performance objectives remains in question. These issues of life safety and predictable response are addressed in this paper through an investigation of a modern-day FBD code.

Earlier efforts in this direction include – but are not limited to – the work by Mehanny et al. [1] and Rivera et al. [2]. The former [1] was mainly geared towards calculating estimates of force modification and displacement amplification factors (R and C_d, respectively, known as R and R_d in ECP 201 [3], and q and q_d in EC8 [4]) for composite RCS and Steel moment frames designed as per US standards (e.g., [5,6]), and comparing them to their corresponding values specified in the adopted design codes in order to assess how such provisions were successful to deliver safe, reliable and economic designs. On the other hand, the recent work by Rivera et al. [2] focused on trying to furnish an answer to the question that naturally arises: "Are FBD provisions of modern seismic codes compatible with PBD objectives?". They therefore investigated the predictability of response and margin of safety of trial designs of regular medium ductility RC moment

---

[*] Corresponding author. Tel.: +20 12 444 8008.
E-mail addresses: sameh.mehanny@stanfordalumni.org, smehanny@darcairo.com (S.S.F. Mehanny).

0141-0296/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2010.04.014

framed structures designed according to [4]. Their assessment was performed by comparing the design displacements and forces for these frames to those obtained from nonlinear time history analysis.

The current paper is an additional effort along the same frontier looking into semi-empirically based key factors R and R_d used for FBD procedures. The research focuses though on investigating only low- to mid-rise ductile RC moment resisting frames located in moderate seismic zones (0.25 g), and further studying the implications that the frames' configuration (perimeter versus space frames) may have on the overall response. Seismic provisions of interest for this study are the emerging Egyptian seismic provisions [3] that are largely compatible with EC8 main directions. The ultimate goal is to evaluate the current code-specified R and R_d factors, and to eventually improve the reliability of constructed facilities designed using FBD methodologies.

Four Code-Compliant-Design (CCD) versions of RC ductile moment resisting frame buildings (4-, and 8-story, adopting perimeter and space frames' configurations) are developed using ECP 201-FBD provisions. Using nonlinear analyses involving inelastic static pushover analysis and incremental dynamic time history analysis under a suite of 20 multi-level scaled records, static and dynamic contributions to inelastic force reduction are identified and compared to code/regulations-specified assumptions. Fragility curves for the frames are also developed corresponding to various universally code-specified performance levels encompassing, for example, Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) as identified by FEMA 356 [7]. Generated information facilitates retrieving relevant actual inherent R and R_d factors and comparing them to code pre-specified values adopted earlier in the FBD process. A Modified Code Design (MCD) procedure relaxing design drift demands for the investigated buildings (and hence overcoming a specific deficiency in the current requirements of the ECP 201 seismic provisions as will be demonstrated in what follows) is proposed in the current research and is further examined to test its effectiveness and reliability.

2. Outlines and specifics of the seismic design procedures

The main design requirements specified in [3] are the "no-collapse" and the "damage limitation" requirements. Satisfying the "no-collapse" requirement depends mainly on the strength of the designed elements to resist all expected stress resultants that occur due to the seismic actions. Design seismic actions correspond to the reference seismic hazard associated with a reference probability of exceedance of 10% in 50 yrs (or a reference return period of 475 yrs). In a complementary step, and in line with EC8 regulations [4], the structure shall be also checked to withstand a seismic action having a larger probability of occurrence (minor earthquake) than the design seismic action associated with the "no-collapse" requirement, without occurrence of damage to structural and non-structural elements. Such seismic action is used to verify the "damage limitation" requirement. It has a probability of exceedance of 10% in 10 yrs (or a return period of 95 yrs) and is almost equal to half of the design seismic action for the "no-collapse" limit state taking into account the importance factor of the building. As per code, the "damage limitation" requirement is satisfied if the interstory drifts are limited to a given fraction of the story height depending on the type and fixation form of the non-structural elements. The interstory drift associated with the design seismic action for the "no-collapse" limit state has thus to be first reduced to take into account the lower return period of the seismic action associated with the "damage limitation" requirement. Implicit in the use of this reduction is the assumption that the response spectrum of the seismic action for the "no-collapse" requirement has the same shape as the spectrum of the seismic action for "damage limitation" requirement (i.e., the latter is a scaled down replica of the former). For buildings investigated herein, this reduction factor, ν, is taken equal to 2.0 [3] and the interstory drift limit is set to 0.5% associated with non-structural elements of brittle materials that are attached to the structure. It is worth pointing herein that in other similar seismic provisions commonly adopted worldwide especially in the US practice (such as in [5,8,9]), instead of performing the drift checks for a minor earthquake with a larger probability of occurrence (10% in 10 yrs) than the design level earthquake used for strength checks (i.e., the 10% in 50 yrs event), and accordingly reducing the interstory drift limit or capacity (e.g., 0.5%), they rather perform the drift (and strength) check(s) for one same design level earthquake of 10% in 50 yrs but with a magnified interstory drift limit. This magnified limit is roughly equal to the limit set by Eurocode (as a ratio of the story height) times the υ factor mentioned above. In other words, even though different codes apparently approach the same task from different perspectives, they are basically more-or-less heading towards the same target.

Note that, furthermore, in order to avoid excessively low design acceleration values (and hence potentially non-conservative designs in terms of lateral strength/resistance) for medium- to long-period structures that may arise from inaccurate modeling, and again similar to Eurocode directions in that concern, ECP 201 is imposing a constant minimum design acceleration of $0.2a_g$. Such enforced lower bound sometimes introduces too much conservatism into the design which will be examined in the course of this research.

Two seismic design scenarios are performed in this paper on four case study buildings. The buildings consist of 4- and 8-story moment framed ductile RC structures adopting either space or perimeter frames' systems. The two seismic design procedures are depicted below:

1. Code-Compliant Design (CCD):

It is a design procedure where (1) "no-collapse" – in terms of satisfying strength of different structural elements considering second-order effects – and (2) "damage limitation" – in terms of satisfying code interstory drift limits under reduced hazard – requirements are jointly satisfied. Code Design Response Spectrum (DRS) modified by the response modification factor, R, as shown in Fig. 1(a) and featuring the constant acceleration lower bound of $0.2a_g$ is adopted.

2. Modified Code Design (MCD):

It is a modified (more relaxed) seismic design procedure through ignoring the code pre-specified constant acceleration lower bound when checking drift demands. This concept is not uncommon in well established international seismic design provisions (e.g. [5,8,9]). In other words, checking drift is carried out for a scaled down version of the code acceleration Elastic Response Spectrum (ERS) associated with 10% in 50 yrs hazard as shown in Fig. 1(a) by directly dividing its ordinates by the R factor, as well as by a reduction factor $\nu = 2.0$ [3] accounting for the lower return period (corresponding to a 10% in 10 yrs hazard) of the seismic action associated with the code "damage limitation" requirement, then magnifying it back by a displacement behavior factor, R_d, approximately equal to $0.7R$ [3]. The resulting Modified Elastic Response Spectrum, MERS [$=\text{ERS} \times (1/\nu) \times (Rd/R)$] used for checking drift and developed in the context of this step is shown in Fig. 1(a) for comparison purposes. This proposed step entirely discards any effect on seismic design drift demands that may arise from the lower bound of $0.2a_g$ on the design acceleration specified by code and reflected into the code DRS. However, the "no-collapse" requirement is still verified for the code acceleration DRS with the lower bound on the design acceleration. MCD procedure, despite being a code non-compliant design procedure, is promoted herein since it provides potentially economic versions of the case study buildings yet without risking safety as will be demonstrated later.