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Response modification factor of concentrically braced frames with hexagonal pattern of braces

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the response modification factor 'R' of the new bracing configuration of concentrically braced frames (CBFs). This innovative bracing system called "hexa-braced frame" is composed of hexagonal pattern of braces in which vertical structural elements connect the V and inverted-V bracings over three stories to form the hexagonal bracing configuration. FEMA P695 provides a global methodology to quantify seismic performance factor for new structural systems. Following this methodology, a set of 4-, 10- and 20-story archetypes representing low-, mid- and high-rise buildings, respectively, were used to evaluate the R factor of the hexa-braced frame. Trial values of R factor were examined through nonlinear static and dynamic analyses to satisfy acceptance criteria of the P695 methodology. The results were compared with the responses of similar X-braced frame models as the benchmark. The iterative process to determine R factor for the hexa-braced frame was performed using values of R factor, 6 and 7. Based on the performance evaluation of hexa- braced frame archetypes by measuring their collapse fragility, the value of R factor, 7 achieved the safety margin against collapse during the earthquakes. As expected, the analysis results confirmed the given value of R factor 6 for X-braced frame system in design codes (ASCE 7).

1. Introduction

The common seismic design method in current codes (NEHRP, BOCA, UBC, IBC and ASCE/SEI) is based on the equivalent static analysis due to its simplicity. In this method, a reduction factor or response modification factor, R, reduces the linear design spectrum while accounting for nonlinear behavior and ductility capacity of the seismic resisting system to achieve lateral design forces [1].

The R factor first introduced in ATC-3-06 report [2] is based on the past earthquake observations. Thereafter, many other researches were developed to evaluate this factor [3–7]. From the results of these researches, ATC-19 [8] and ATC-34 [9] proposed that the R factor was as the product of three factors including ductility, R_μ, over strength, R_o, and redundancy factor, R_r, (Eq. (1)) which is calculated based on the nonlinear static analysis results.

$$R = R_o R_\mu R_r \tag{1}$$

Though this traditional method is quite simple, however, the reliability of values assigned to these factors are unknown [10]. This conclusion is drawn from the comparison of the performance of the buildings during past earthquakes and their expected performance from seismic design. Thus, with the rapid growth of new structural systems, a general methodology is needed to determine the response modification factor. A contract was awarded to ATC-63 by FEMA to provide a global methodology for the quantification of seismic performance factors of the buildings (FEMA P695) [11]. This methodology determined the seismic factors for new structural systems to prevent building collapse in the severe earthquake equivalent to the maximum considered earthquake (MCE). This was consistent with the design criteria of NEHRP Provisions. The P695 methodology quantified the uncertainties involved during the procedure to more reliably achieve safety performance of buildings against earthquake. Several studies have been conducted to develop FEMA P695 methodology. Hamidia et al. [12, 13] proposed a simplified method to assess the collapse capacity of the buildings without running nonlinear time history dynamic analyses and based on the results of nonlinear seismic responses of single-degree-of freedom systems. Liel and Tuwair [14] recommended a trial method to calculate the collapse capacity of the structures subjected to a set of ground motion records without running an IDA. Eads et al. [15] presented an approximate method for providing the fragility curve to evaluate collapse behavior of the structures. Hardyniec and Charney [16] presented a simple toolkit for performing FEMA P695 process.

It is obvious that the response modification factor of a seismic resisting system plays a key role in predicting the seismic performance of the buildings during an earthquake. Common seismic design codes

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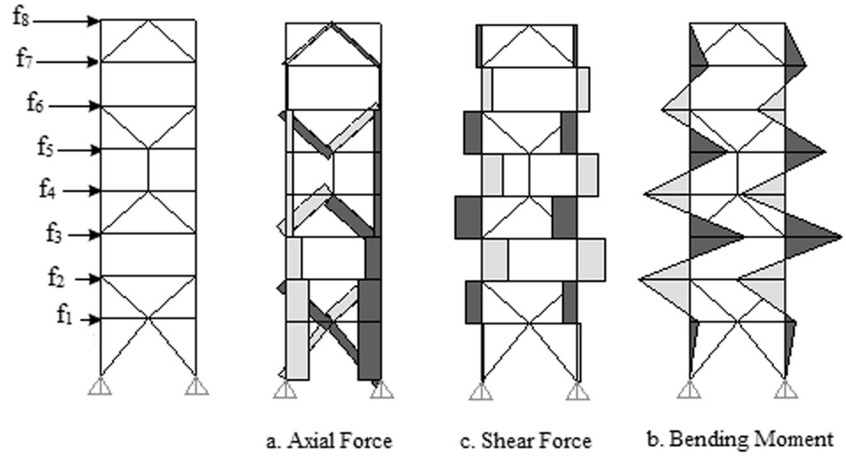

Fig. 1. Internal forces of Hexa-braced frame under lateral loading.

[17] assigned the R factor for current steel structural systems including moment resisting frames, concentrically and eccentrically braced frames, special truss moment frames, steel plate shear walls and buckling restrained braced frames. Amongst all the steel structural systems, concentrically braced frames (CBFs) are widely used as seismic resisting systems [18, 19]. There is a deficiency with the seismic ductility capacity for CBFs. To resolve and fix this problem, several configurations including X, V, inverted V, Y, knee braces, etc. have been developed. While new bracing configurations of CBFs are being changed, seismic design codes give a constant value of R factor for CBFs neglecting bracing configurations. Therefore, determination of R factor for new structural systems is based on the engineering judgments and comparison with the response of known structural systems defined by the seismic codes. Based on economical and architectural requirements many studies have evaluated the impact of different bracing configuration on the seismic coefficient [20–28].

The objective of this research paper is to assess the response modification factor, R, of the new bracing system called hexa-braced frame following the FEMA P695 methodology. The hexa-braced frame is a modification of concentrically braced frames (CBFs) that has the hexagonal pattern of a bracing scheme. It contains both V- and inverted V-braces in different stories, forming the hexagonal bracing configuration over three stories. Recently, the use of hexagonal patterns for structural effectiveness and aesthetics has attracted the attention of engineers [29, 30]. For example, the hexagrid system has been employed as a lateral resisting system for tall buildings as a tube type structural system [31–33]. Thus, the research on the hexa-braced frame system can be attractive for the interested readers. To this end, a set of 4-, 10- and 20-story building models were analyzed to examine the trial values of R factors for different building heights representing low-, mid-, and high-rise buildings, respectively, compared to similar X-braced frame models as the benchmark.

2. Hexa-braced frame system

The hexa-braced frame is a bracing system that has the hexagonal pattern of braces in which vertical structural elements (strong column or tie column) in a story connect the V and inverted-V bracings at the stories below and above that story, respectively. The tie columns behave like the zipper columns, therefor; they are designed to have enough strength so as to resist the unbalanced load. They are also used in conjunction with a beam (compared to CBF beams), allowing the tie to engage the braces in an adjacent story by pushing up or down on the beam. In this system, beams are joined to the column with simple pinned connections. This is a combined system comprising continuous columns and braces for seismic resistance. Although all beam connections are simple, continuous columns can carry the bending moment as well as the axial force induced by the seismic loads due to the bracing configuration (Fig. 1). The design of CBF columns for seismic resistance is based on truss action and is governed by the column axial forces. Therefore, the reaction forces make the columns stronger than the conventional braced frame columns. Fig. 2 shows that there are two possible bracing configuration of hexa-braced frame. These, two types of chevron and diagonal braces are used to form the hexagonal bracing configuration based on the length of the braced bay.

3. Overview of the FEMA P695 methodology

The standard methodology for determining seismic performance factors of buildings was provided by FEMA P695. The general procedure of this methodology is illustrated in Fig. 3. This method is a trial approach which begins by considering an initial value of R factor. Moreover, some information about the intended structural system is gathered in the first step. The index archetypes then were selected as they can cover all the characteristics of the structural system. Eventually, in order to obtain reliable results, the uncertainty values related to test data (β_{TD}), design requirements (β_{DR}) and modeling method (β_{MLD}) applied providing index archetypes was considered during the procedure. After the archetypes were developed, nonlinear static (pushover) and incremental dynamic (IDA) analyses were performed. From the analysis results and through a probabilistic procedure, the considered R factor applied in the seismic design of archetypes was evaluated and

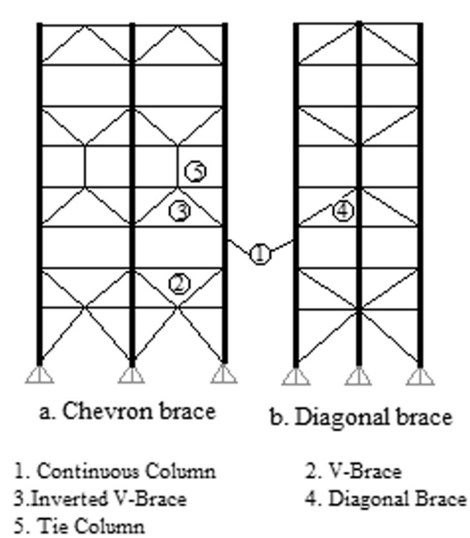

Fig. 2. Different hexa-bracing configurations.