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Methods for the Determination of the Response Reduction Factor of the Seismic Forces

Grisel Morejón-Blanco[1], Carlos Llanes-Burón[2], Zenaida Paulette Frómeta-Salas[3]

1. Centro Nacional de Investigaciones Sismológicas (Cenais), Cuba.
2. Universidad Tecnológica de La Habana José Antonio Echeverría (Cujae); Centro Nacional de Referencia para la Prevención y Mitigación de Desastres (PREMIDES), Centro de Estudios de Construcción y Arquitectura Tropical (CECAT), Facultad de Ingeniería Civil, Cuba.
3. Universidad de Oriente, Facultad de Construcciones, Cuba.

Abstract: The various analytical methods and procedures for determining the response reduction factor for seismic forces in buildings are presented. A critical analysis of the earthquake-resistant design codes of different countries is then conducted, with the aim of determining how they consider the response reduction factor. The main positive aspects for their possible use in the Cuban Earthquake-Resistant Code are also analyzed.

Key words: response reduction factor; ductility; overstrength

1. Introduction

Currently, earthquake-resistant design considers that the lateral resistance required for a standard occupancy structure to achieve adequate structural performance when subjected to seismic excitation decreases as its plastic deformation capacity increases. Based on this, the seismic design of structures considers the possibility of providing them with a significant plastic deformation capacity as a way to maintain their design lateral resistance within a range of values, thus making their design economically affordable.

One of the consequences of allowing structures to significantly exceed their post-elastic behavior range is the occurrence of significant structural damage, which can lead to undesirable situations, such as high rehabilitation costs and poor non-structural performance (Arroyo and Terán, 2002).

Large earthquakes highlight the errors made in the design and construction of buildings. Obviously, the incorrect selection of construction materials is a crucial source of error. During the seismic disasters that have occurred around the world in recent decades, very serious failures have occurred in reinforced concrete structures; among these:

- Brittle shear failure in short columns due to the restraining effect of nonstructural elements.
- Brittle failure in coupled shear walls with or without openings.
- Failure due to sudden stiffness changes along the building's height.
- Brittle failure due to shear and diagonal tension in columns and beams.
- Beam-column connection failure.

The seismic behavior of reinforced concrete structures has been analyzed more than that of any other type of structure.

This is due, on the one hand, to their widespread use and, on the other, to the difficulty of providing them with a certain degree of ductility, overstrength, and redundancy, allowing them to behave adequately during a severe seismic event.

For reinforced concrete structures to exhibit good seismic performance, they must possess at least a minimum level of ductility. This characteristic refers to the ability of the components of a structural system to alternately enter the inelastic domain without appreciable loss of their load-bearing capacity (NC 46:2017). It is an important property in a structure subject to the effects of an earthquake, as it eliminates or reduces the possibility of sudden brittle failure; it also provides an additional source of damping.

The concept of ductility was first incorporated into design codes in the 1970s (ATC-1974). Therefore, buildings designed before this period can be expected to be highly vulnerable if seismic demands tend to reach their quasi-elastic bearing capacity. This has been repeatedly corroborated after the occurrence of destructive earthquakes, such as those in Northridge (1994), Kobe (1995), China (1996), Turkey (1999), China Taiwan (1999), among others.

Overstrength is a consequence of the sequential formation of plastic hinges in an adequately detailed redundant structure. It depends on the uncertainty of the structure's execution and manufacturing and is also acquired in the design by selecting larger quantities than theoretically required.

Redundancy is the ability of a structure to redistribute loads from the most stressed elements to the least stressed elements.

2. Methodology

To achieve the proposed objectives, a bibliographic review was conducted of the different analytical and experimental methods and procedures for determining the response reduction factor. Subsequently, an analysis was conducted of the earthquake-resistant codes of developing countries in the field of seismic engineering, with the aim of determining how they consider the response reduction factor. Their main limitations and positive aspects for their possible use in the Cuban Earthquake-Resistant Code were also analyzed. The following procedure was adopted:

- Assessment of the reference framework for determining the response reduction factor for seismic forces.
- Critical review of the methods for determining the response reduction factor.
- Critical review of the main earthquake-resistant design codes of developing countries in earthquake-resistant engineering.

3. Results and Discussion

In the seismic analysis and design procedures for buildings, it is necessary to introduce simplifications or approximations that allow determining the equivalence between elastic analysis, based on which structural designs are based, and elastoplastic behavior, the actual behavior of buildings when subjected to earthquakes.

One of these simplifications consists of designing structures to have lateral resistance lower than the elastic resistance. This is achieved by applying lateral forces calculated from inelastic design spectra, which are elastic design spectra modified by response reduction factors.

This is because the design spectra of seismic codes assume a return period of 475 years for an ordinary structure—a probability of occurrence that is very low during the structure's useful life. Therefore, structures are designed to sustain damage without collapsing under the design spectrum. Thus, in the event of an earthquake meeting the regulatory requirements, the structure may suffer damage, requiring the structural designer to ensure sufficient ductility, adequate overstrength, and redundancy.

To illustrate the above, the upper curve shown in Figure 1 corresponds to the elastic design spectrum of soil S2 of NC 46:2017. If a structure is designed with this spectrum, it will not suffer damage in the severe earthquake of the code, which has a return period of 475 years. However, the structural elements will be of considerable size, and the design will be uneconomical, as the seismic forces are quite high. If the structure is designed for the inelastic spectrum, indicated in the lower curve of Figure 1, which is obtained by dividing the ordinates of the elastic spectrum by the ductility reduction factor, the seismic forces will be lower.

From the above analysis, it follows that if the value assigned to the ductility reduction factor is high, the seismic forces will be low. On the contrary, if this factor is low, the seismic forces will be high. Therefore, setting values that are as realistic as possible is the fundamental basis for estimating design seismic forces.

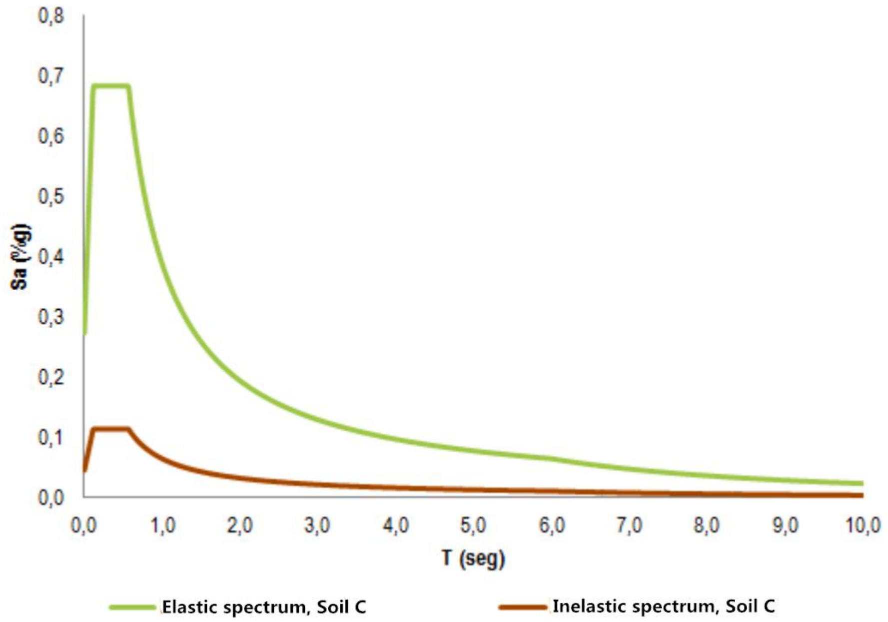

Figure 1. Elastic and inelastic soil spectra, Class C of NC 46:2017.

Extensive research has been conducted on the validity of response reduction factors, which allow for the design of buildings with nonlinear response using linear analysis tools. Initially, these factors were formulated solely based on ductility.

In recent decades, considerable work has been done to quantify the seismic force reduction factor (R), and several theoretically and experimentally supported formulations have emerged. The first of these was proposed by Bertero, Anderson, Krawinkler & Miranda (1991), Miranda (1997), and Whittaker, Hart & Rojahn (1999), who recognized that the R factor is the product of four factors (Equation 1).

$$R = R_{\mu} R_{\Omega} R_{VG} R_{R} \qquad \text{Equ. 1}$$

Where: R_{μ} is the ductility strength reduction factor, obtained from the single-degree-of-freedom system; R_{Ω} is the overstrength factor, defined as the ultimate capacity of the structure with respect to the design capacity; R_{VG} is a reduction factor that takes into account that the structural system has several degrees of freedom and R_R is the redundancy factor that indicates the efficiency of non-structural elements to transmit loads in the non-linear range.

Another formulation very similar to the previous one is shown in equation 2, stated by Uang (1991), Whittaker et al. (1999) and Elnashai and Mwafy (2002) and in which they change the R_{VG} factor to the damping factor R_{ξ}. When the structure enters the nonlinear range it dissipates energy by hysteresis, the damping factor R_{ξ} increases as the structure is damaged more, the factor R_{μ} is a reduction factor due to energy dissipation. Riddell and Newmark (1979) consider the damping ξ at the value of R_{μ}, so that they obtain a single factor $R_{\mu\xi}$.

$$R = R_{\mu} R_{\Omega} R_{\xi} R_{R}$$ Equ. 2

And finally, the ATC-19 (1995) considers that the R factor is equal to the product of three factors (equation 3)

$$R = R_{\mu} R_{\Omega} R_{R}$$ Equ. 3

Likewise, the factors that influence the determination of the reduction factor are studied; from this, it is concluded that R factors are theoretical and derive their name from the fact that they reduce elastic seismic forces by their value for long-period structural systems; for short-period systems, the reduction is smaller, although it is still associated with this factor.

The behavior of different types of structures under cyclic stresses produced by seismic actions inevitably results in a certain reduction in stiffness and strength, consequently reducing the system's energy dissipation capacity. Therefore, it is essential to estimate or establish allowable reductions based on certain real or synthetic earthquake records. It has been proven very difficult or almost impossible to establish precise criteria that consider the structure's natural lifespan and the probable duration of an earthquake, and thus the possible number of stress cycles.

Building codes implicitly or explicitly acknowledge that under severe seismic actions, ordinary structures will experience significant inelastic behavior. For this reason—as previously mentioned—most codes employ elastic response spectra in their design procedures, incorporating a response reduction factor ensured by the seismic-resistant system. Consequently, these conditions can be regarded as preceding the collapse limit state. Indeed, a substantial portion of material losses stems from building collapse risks. This demonstrates that predicting this limit state involves greater uncertainty and necessitates special considerations.

To this end, codes use various design criteria depending on the characteristics of each country and the information and resources available. Therefore, there is a wide variety of methods and methodologies for determining each of the parameters that affect the seismic safety of structures. A critical analysis of how the R factor is treated in the earthquake-resistant codes of different countries is presented below.

In the Cuban Earthquake-Resistant Code (NC 46:2017), force reduction is quantified by the Ductility Reduction Coefficient (R_d), which describes the expected overall ductility of the earthquake-resistant system and is simply the ratio between the actual maximum displacements and the calculated displacements, assuming linearly elastic behavior of the structure. These values mean that the seismic forces used in the design do not correspond to those required to guarantee adequate performance of structures in the event of large-magnitude earthquakes. These values, extrapolated from other regulations, do not take into account that they depend on the ductility, overstrength, and structural redundancy of the materials and construction systems. This can lead to structural failure and the resulting loss of human life and property.

The values tabulated in the code depend on the type of structure and the seismic design level. It should be noted that this code does not explicitly consider the overstrength of materials, but does so implicitly, as it classifies structural systems based on their structural material.

The earthquake-resistant codes of countries with developed seismic engineering were reviewed, highlighting their main limitations and positive aspects for use in future updates of the Cuban Earthquake-Resistant Code. The following results were obtained from this analysis.

- The first important aspect is that in all the codes reviewed, the response reduction factors for steel structures are higher than those for concrete structures; furthermore, some codes consider values for structural systems commonly used in building design.
- In most codes, such as those in Latin America, the reduction factors depend solely on ductility, for which design

levels are established at the design stage. Only in Eurocode EC-8 (Comité Européen de Normalisation [CEN], 2012) do the reduction factors depend on overstrength and damping, considering multiplying coefficients that vary according to structural redundancy and structural materials; although it should be noted that no direct reference is made to this factor in the code.

- The Spanish NCSE Code (Spain, Ministry of Public Works, 2002) is the only one that does make a direct reference to the influence of damping in the calculation of the reduction factors. However, it recommends the average value classified according to the structural material, without referring to considerations of values that depend on the influence of non-structural elements, such as the density and distribution of masonry walls, which have been shown to alter the expected damping values of structures.
- The amplification of seismic motion for different soil types is explicitly considered in Eurocode EC-8 (CEN, 2012) and in the Venezuelan COVENIN 1756 (Caracas, Venezuela, Ministry of Urban Development, 2001), by adopting dynamic amplification factor values that depend on geotechnical characteristics, represented by shear wave velocities and stratum thicknesses. The Spanish NCSE code (Spain, Ministry of Public Works, 2002) presents similar maximum amplification values for the soils considered in the code.
- There are few explicit references in earthquake-resistant codes to the influence of structural redundancy on response reduction factors. Redundancy is not well defined in earthquake-resistant design standards, and its effect is generally associated with reduction factors for strength reserves. While there is a widespread belief about the benefits that strength reserves provide to the ductile response of structures, there are few clear references to how they should be calculated and explicitly incorporated into the design.
- The most recent codes are beginning to incorporate aspects suggested in recent studies, such as structural redundancy. An example of this is the factors that increase the reduction factors in Eurocode EC-8 (CEN, 2012) and the Colombian NSR-10 when structures meet certain redundancy characteristics of vertical resisting elements. These factors, although approximate, are also observed in the International Building Code (IBC) (2003) and NC 46: 2017. Despite this, the criteria used, which essentially consist of reducing the response reduction factor R, are empirical and do not allow the designer to appropriately modify or select the redundancy factor based on the characteristics of the building being analyzed.
- Structural regularity is directly considered in Eurocode EC-8 (CEN, 2012), the Colombian and Dominican Codes, the new Cuban Code, and the Japanese Code; in the rest of the codes analyzed, it is only considered indirectly.

4. Conclusions

The theoretical response reduction factors used in codes to reduce elastic seismic forces use constant values for both long- and short-period structural systems.

Analyzing the behavior of different types of structures under cyclic stresses produced by seismic actions inevitably leads to a need to reduce stiffness and strength, thereby reducing the system's energy dissipation capacity. Therefore, it is essential to establish allowable reductions.

Many codes fail to consider force reductions due to inelastic behavior only in relation to maximum values of deformation or dissipated energy.

In most current seismic codes, the period, damping, and soil type at the site are not explicitly considered in the response reduction factor, which leads to inadequate designs.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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