Engineering Structures 59 (2014) 495–506

Contents lists available at ScienceDirect

Engineering Structures

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

Multi-performance seismic design through an enhanced first-storey isolation system

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A R T I C L E I N F O

Article history:
Received 18 July 2012
Revised 30 October 2013
Accepted 4 November 2013

Keywords:
First-storey seismic isolation
Performance based design
Capacity spectrum method
Crescent shaped braces

A B S T R A C T

In this paper the idea of the "shock-absorbing soft storey concept", originally proposed at the end of 1960s by Fintel and Khan, is reviewed and developed within the framework of performance based seismic design. The purpose is to conceive a first-storey isolated building capable of satisfying selected seismic performance objectives. Among all the possible solutions, in this study the seismic story isolation is obtained through the insertion (only at the bottom level of the building) of special hysteretic devices, which are specifically designed in order to satisfy the prefixed seismic performance objectives. Without loss of generality, this design approach is fully detailed with reference to the specific case study of a five-storey steel frame building. The performances of the building under multiple earthquake design levels are finally verified through non-linear time-history analyses whose results confirm the effectiveness of the proposed approach.

1. Introduction

The design of building structures capable of providing prescribed seismic performances is the fundamental objective of the Performance Based Seismic Design (PBSD) approach [1,2]. The bases of the PBSD lie in the capacity of defining and satisfying a plurality of performance objectives [2], i.e. in the capacity of predicting that a given structural system will perform in a selected manner (i.e. performance level) under a given seismic intensity (i.e. earthquake design level).

Typically, the traditional seismic design of the structures is carried out using a Force Based Design approach (FBD, borrowed from the common approach for static design). Moreover, the load-bearing system (designed for vertical loads) typically withstands also the horizontal loads (i.e. it accomplishes the function of the horizontal resisting system). In such a way, the same structural system acts for both vertical and horizontal actions and therefore cannot be designed in an "optimized way". Nonetheless, the dynamic response of the whole system is somehow passively evaluated and not "governed" by the designer.

On the other hand, in the last decades, several contributions in the field of earthquake engineering introduced new design approaches in order to provide the structural system able to behave in a prescribed way under an earthquake of a given intensity. Among others, the most remarkable are: (i) the PBSD approach [1,2] that, as mentioned before, formalized the need of satisfying a multiplicity of performance objectives, (ii) the Direct Displacement Based Design (DDBD) [3] that introduced the displacement analysis as a tool for seismic design of structures, (iii) the Capacity Spectrum Method (CSM) [4,5] that is a graphical design representation which allows to compare the "capacity of a structure to resist lateral forces to the demands of earthquake response spectra in a graphical presentation that allows a visual evaluation of how the structure will perform when subjected to earthquake ground motion" [5]; (iv) the use of dissipative devices (e.g. unbonded braces, dampers, ... [6]) or seismic isolators [7] adopted for the mitigation of the seismic effects upon the structure, that may lead to a more easy conceptual separation between the horizontal and vertical resisting systems; (v) the soft storey conceptual design for earthquake-resistant structures can be achieved "by designing a shock-absorbing soft storey" upon which the structure will remain within the elastic range, so that high intensity earthquake motions are confined "to controlled areas in the lower part of the building" [8].

Even if all these contributions are well consolidated among the scientific community, in the scientific literature an overall design approach which combines the above-cited contributions is not present. This paper presents an approach for a full-controlled optimized seismic design of structures which applies the original idea of the soft storey seismic isolation within the framework of the performance based seismic design. In detail, for sake of clearness but without loss of generality, the seismic design approach will be fully developed with reference to a specific case study.

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0141-0296/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.engstruct.2013.11.002

2. Background

2.1. The concept of shock-absorbing soft storey

The basic idea which is here developed in order to conceive an optimized seismic design approach is borrowed from the so called “shock-absorbing soft storey concept”, originally proposed at the end of the 1960s by Fintel and Khan [8]. In the cited work, the authors proposed a new concept for earthquake-resistant structures based on controlling the lateral forces and accelerations induced in the structure by the earthquake. The limitation of the lateral forces is achieved by designing a shock-absorbing soft storey with a bi-linear force–displacement behaviour. This system allows to concentrate all the inelastic deformations (or undesirable effects) due to high intensity earthquake at the soft storey (typically the first storey) only. Above the soft storey the structure is designed in order to remain elastic. In the original paper [8] the authors proposed a system composed of stability walls within the soft storey able to withstand a portion of the overturning moments induced by the earthquake, while elastomeric strips were proposed in order to accommodate the large distortions. Such a system should allow to reduce or, at limit, to avoid damages on the superstructure. In this framework, the most significant seismic design variable is the yielding strength of the soft storey.

2.2. The performance based seismic design

The basic concept of PBSD relies primarily on the identification and definition of multiple performance objectives. This philosophy was first formulated in the Vision 2000 document [1]. A performance objective is a coupling of an expected building performance level (considering both the structural and non-structural response) to a prescribed level of seismic intensity [2].

For a common building the following “basic performance objectives” are generally required [1]:

- PO-1: “Frequent Earthquake (FE) + Fully Operational (FO)”: under a frequent earthquake negligible damage for both structural and non-structural elements can occur, and facilities can continue with no disruption.
- PO-2: “Occasional Earthquake (OE) + Operational (O)”: under an occasional earthquake negligible damage for structural elements and moderate damage for the non-structural ones can occur, and facilities continue in operation with minor damage and minor disruption only in non-essential services.
- PO-3: “Rare Earthquake (RE) + Life-Safe (LS)”: life safety is substantially protected, damage to structural and non-structural elements is moderate to extensive.
- PO-4: “Very-Rare Earthquake (V-RE) + Near-Collapse (NC)”: life safety is at risk, damage is severe but structural collapse is prevented.

Fig. 1 illustrates the performance based seismic design framework.

3. The enhanced first storey isolation system

3.1. The idea and its development

The conceptual structural design that is here proposed is based on the original idea of the soft storey concept for the mitigation of the seismic effects, which is revised and developed within the PBSD framework. The coupling of these two fundamental concepts is graphically represented in Fig. 2 and leads to the structural solution that may be referred to as “enhanced first-storey seismic isolation” (right-hand scheme of Fig. 2), which is inspired by the structural schematization provided in Fig. 6 of the work by Fintel and Khan [8].

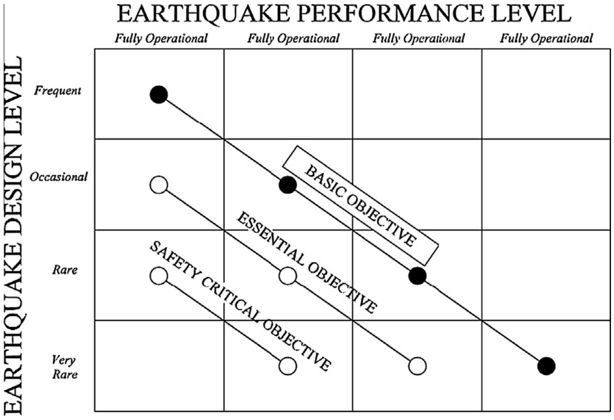

Fig. 1. Performance based seismic design objectives.

An enhanced first-storey seismic isolated building is characterized by the following resisting systems:

- Vertical-load Resisting System (VRS), typically beams and columns, which is specifically designed to withstand the static vertical loads.
- First-storey Horizontal-load Resisting System (HRS), consisting of special dissipative devices located only at the first storey, which is specifically designed in order to accomplish multiple seismic performance objectives.
- Bracing Rigid System (BRS) of the superstructure, consisting in common stiff braces, which is designed in order to behave in the elastic field and provide the superstructure with enough lateral stiffness with respect to the stiffness of the bottom storey.

The fundamental advantage which emerges from this rationale is the separation (from a design point of view) of the VRS and HRS systems. In such a way the HRS can be designed specifically to accomplish only seismic requirements (without accounting also for static design issues, which are provided by the VRS only).

The main objective of the present paper is to describe a design approach which allows to obtain a structure with a preselected behaviour under multiple seismic intensity levels. The approach is then fully developed with reference to a specific steel structure.

3.2. The structural idealization

Thanks to the presence of the superstructure bracing system (provided that the braces are sufficiently stiff and properly arranged, as we suppose here), the upper storeys can be considered as a single rigid block compared to the first floor, thus allowing a single-degree-of-freedom (SDOF) idealization. Clearly, the SDOF schematization can be considered reasonable if the global rotation of the superstructure (assumed as a rigid body system due to the presence of the stiff diagonal bracings) is limited. This condition has to be checked by the designer (here we assume that the condition is satisfied). According to this idealization, Fig. 3 graphically represents the analogy between the actual structural system and its equivalent SDOF idealization: the mass m of the SDOF is equal to the total building mass, while the lateral stiffness K is equal to the first-storey lateral stiffness, which is given by the sum of the HRS lateral stiffness, k_{HRS} (that typically represents the predominant contribution), and the VRS lateral stiffness, k_{VRS} (that is typically small, but not negligible).