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A State of Art Literature Review on Direct Displacement-Based Design for Seismic Structural Analysis

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Abstract

Earthquakes are one of the most disastrous forces which cannot be stopped or prevented but their effects can be minimized with minimal causalities' of lives and structural damages. Over the past decade, analysis and determination of the seismic site response has gone from a topic of controversy to the mainstream issue addressed in most building codes, research and practice. Structural design has headed a path from Working Stress Design towards Performance-based Design. As design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to stated levels of seismic hazard. Performance levels, indeed, are described in terms of displacements, as damage is better correlated to displacements rather than forces. As a consequence, new design approaches, based on displacements, have been recently implemented. One of such approach is the Direct Displacement-Based Design (DDBD), firstly proposed by Priestley (1993). The fundamental principle of DDBD is to obtain a structure which will reach a target displacement profile when subjected to earthquakes consistent with a given reference response spectrum. An importance of DDBD that has been extracted from different literatures has been described in this paper.

Keywords: Concrete structures, Direct displacement-based design, Displacement, Force-based design, Performance-based seismic design etc…

Introduction

Amongst all the natural hazards, earthquakes are the predominant, leading to critical and major damage to the structures and causalities' to the human beings. The Buildings, which appeared to be strong enough, may crumble like houses of cards during an earthquake and deficiencies are exposed. There is no simple, reliable and full-proof rule that produces a safe and economical structure each time. Since, earthquake forces are random in nature and unpredictable, the engineering tools need to be sharpened for analyzing structures under the action of these forces. Only the right estimate of the earthquake force and reliable seismic analysis finds the way to minimize the damage in casualties and structures.

Designing process for making structure seismic resistance has been undergoing a critical reappraisal in recent years, with the emphasis changing from strength to performance. There is increasing agreement among researchers and professionals that future seismic design needs to be based on achieving multiple performance objectives. During the mid of the 20th century, the period over which the codes adopted specific design calculations for seismic resistance, strength and performance have been considered to be compatible to each other. However, over the past 25 years there has been a gradual shift from this position with the realization that increasing strength may not actually increase safety, neither necessarily reduce damage. This lead to an approach towards a new design concept called "Performance-Based Seismic Design (PBSD)". PBSD is a modern designing concept of seismic resistant structure. Performance-based design is a more general design philosophy in which the design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to stated levels of seismic hazard. Since, 1994 Northridge earthquake and other earthquakes around the world during the end of the 20th century were an eye-opener for the use of PBSD.

Current seismic codes are based on Forced Based Design (FBD). Current force-based design (spectral acceleration-based design) is considerably improved compared with procedures used in earlier years, there are many fundamental problems with the procedure, particularly when applied to reinforced concrete structures. Although the structure is designed to yield during the design earthquake, only the elastic part of the response, up to yield, is examined. The analysis is based on the corresponding secant stiffness. To overcome the problems with FBD a newly design concept has been developed known as Direct Displacement Based Design (DDBD), a part came out from performance-based seismic design, which promise a more rational design philosophy compared to the conventional Force-Based Design (FBD).

Introduction of Direct Displacement Based Design (DDBD)

Performance-based seismic design criteria, intended to produce structures that satisfy specific performance objectives. Performance levels, indeed, are described in terms of displacements, as damage is better correlated to displacements rather than forces. As a consequence, new design approaches, based on displacements, have been recently implemented. One of such approach is the Direct Displacement-Based Design (DDBD), firstly proposed by Priestley (1993). DDBD is based on the observation, that damage is directly related to strain (structural effects) or drift (non-structural effects), and both can be integrated to obtain displacements. The fundamental philosophy behind the design approach is to design a structure which would achieve, rather than bonded by, a given performance limit state under a given seismic intensity. The fundamental difference between FBD and DDBD characterizes the structure to be designed by as a single degree of freedom representation of performance at peak displacement response, rather than by its initial elastic characteristics.

Aim and Objective of the study

The aim of this literature review is to understand the design philosophy and lacuna of force-based design method as well as the importance of displacement criteria in seismic design of concrete structures and understanding the design philosophy of direct displacement-based design method. This literature will enhance the problem identification strategy for the further scope of work.

Literature Review

Literature survey is carried out to know the extent and quantum of work done in a particular area. This particular paper is focussed towards literature study pertaining to DDBD. Literature survey gives ideas about the limit, extent and scope of the work and also helps in framing the objective. Findings of different authors contributed towards direct displacement-based design (DDBD) with their major findings are reported as follows.

Various literatures related to displacement-based seismic design of R.C. structures studied are briefly mentioned below.

Basic concept of Direct Displacement Based Design (DDBD)

- Priestley M. J. N. et al.[9] discussed conceptual problems with current force based design, seismic input for displacement-based design, fundamentals of direct displacement-based design, and analytical tools appropriate for displacement-based design. The design procedure developed is based on a secant-stiffness (rather than initial stiffness) representation of structural response, using a level of damping equivalent to the combined effects of elastic and hysteretic damping. The design method is extremely simple to apply, and very successful in providing dependable and predictable seismic response. The DBD based on elastic response spectra is briefly narrated. DBD based on in-elastic response spectra is also discussed.
- Vidot-Vega Aidcer Linalynn[15] carried out a research work, (1) to study the relationships between material strain and deformation parameters such as curvature and drift for reinforced concrete (RC) moment frame structures and (2) to identify the load history effects on these relationships. Through the use of moment-curvature analysis between strain and curvature for rectangular reinforced concrete sections were explored. The curvature expressions were subsequently used to develop equations to compute inter-storey drift based on strain limits for RC moment frames. The resultant equations can be used in performance-based design approaches such as Direct Displacement-Based Design (DDBD) to compute target drifts and system displacements for prescribed limit states based on material strains. Inter-storey drift ratios for concrete compression and tension steel limits were obtained for different values of longitudinal or mechanical steel ratio. The Inter storey drift, Displacement Ductility and Equivalent Damping were presented as a function of beam aspect (beam length to depth) ratio content here.

Implementation of Direct Displacement Based Design (DDBD) Method

- Chopra A. K. and Goel R. K.[3] developed Direct Displacement-Based Design (DDBD) procedure which is based on the well-known concepts of inelastic design spectra. This procedure provides an accurate value of displacement and ductility demands, and a structural design that satisfies the design criteria for allowable plastic rotation. It was shown that, the existing procedure using elastic design spectra for equivalent linear systems to underestimate the displacement and ductility demands, significantly. It is also that, the existing design procedure is deficient in a sense - plastic rotation demand may exceed the acceptable value of the plastic rotation, than designed. This leads to a false impression that the allowable plastic rotation constraint has been satisfied. The step-by-step procedure to perform DDBD using elastic and inelastic design spectra is presented in literature. Comparison among both the methods has been carried out through illustrative example of Single Degree of Freedom (SDOF) system.

- Pettinga J. D. and Priestley M. J. N. [8] has been used to evaluate the application and effectiveness of the direct displacement-based design (DDBD) method to reinforced concrete tube-frames. Using a set of six uniform structures of 2, 4, 8, 12, 16 and 20 storeys in height, the design method and the inelastic dynamic behaviour have been critically assessed, and where needed procedures have been revised or added to the DDBD process in order to develop a method capable of meeting the specified performance based requirements.
- Sheikh M Neaz, Tsang Hing-Ho and Lam Nelson [14] presents simple expressions for estimating the effective yield curvature for normal- and high-strength circular reinforced concrete (RC) columns based on moment-curvature analyses of 200 column sections. Such expressions can be programmed into the spreadsheet format and can be used for the displacement-based design of RC columns. Influence of different parameters on the effective yield curvature has also been quantified. Effective yield curvature is presented in terms of the gross diameter of the section and the yield strain of the longitudinal reinforcement together with three modification factors that take into account the effects of the compressive strength of concrete, the axial load ratio and the quantity of longitudinal reinforcement.
- Damir Dzakic, Ivan Kraus and Dragan Moric [4] presents the theory and application of this method using a reinforced concrete frame structures. The frame structure is designed with implementing Eurocode 8 regulations. Furthermore, results obtained using direct displacement based design method are compared to the ones obtained using multimodal response spectrum method. The DDBD is defined in great measure and well accepted in science, but the traditional and well accepted force based method found its place in practical engineering. It offers significant control over the analysis and design. Unlike the force based method, in DDBD the limit states are not checked, rather those are used as an input data.

Comparative Studies

- Psycharis Ioannis N. [13] did comparative study by two approaches. (1) Check of an already predesigned structure and make improvements (increase dimensions of cross section) only to members that have problems. (2) Design from the beginning the structure for a certain displacement (Direct Displacement-Based Design - DDBD). The design displacement is usually determined by serviceability or ultimate capacity considerations. He concludes that the use of displacement design spectra is problematic, due to many uncertainties. The plastic rotation capacity of a section is not easy to be calculated (empirical formulas exist for simple cross sections only). DDBD might not converge in some cases.
- Priestley M.J.N., Grant D.N. and Blandon C.A. [10] shown that the emphasis on secant stiffness to maximum displacement, rather than initial stiffness (as in force-based seismic design) is important for rational force-distribution to different seismic-resisting structural elements, and in most cases obviates the need for iteration in the design process, which is inherent in displacement-focused force-based seismic design. It is shown that the influence of hysteretic characteristics has been underestimated in recent force-based studies. These assertions are supported by results of recent analytical studies, which have included refinement of ductility/equivalent-viscous damping relationships, and an examination of the important (and largely ignored) role of

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"elastic" damping in inelastic time-history analyses. There are significant differences between FBD and DDBD. It was shown that, as currently formulated, FBD requires significantly more design effort than DDBD, though FBD can be reformulated so that the design effort is similar. Rational reasons were advanced for distributing seismic forces between structural elements based on secant stiffness to the design displacement, (as in DDBD) rather than on initial stiffness (as in FBD). It was shown that conclusions from earlier time-history analyses may be suspect because of the use of initial-stiffness proportional elastic damping, rather than tangent-stiffness proportional damping. Analyses using tangent-stiffness damping indicate that commonly accepted relationships between elastic and inelastic displacements are inappropriate.

- Cardone D., Dolce M. and Palermo G. [2] presents DDBD procedure for RC framed buildings with different Isolation Systems (IS's) has been presented. The procedure has been specialized for five different force-displacement models of IS, which can be used to describe the cyclic behaviours of a wide variety of IS's, including: (i) High Damping Rubber Bearings, (ii) Lead Rubber Bearings, (iii) Friction Pendulum Bearings and (iv) combinations of Flat Sliding Bearings with different auxiliary devices. The key parameters of the proposed procedure are the target IS displacement (Dd) and the target maximum inter-storey drift (θd), which are assigned by the designer to accomplish either an "Operational Building" (FEMA, 2000) Performance Level (PL), characterised by minimal or no damage to the building structural and non-structural components, or a "Damage Control" (FEMA, 2000) Structural PL, with limited ductility demand to the structural members. At the moment, the design procedure has been fully developed and implemented for the first PL. The implementation for the second PL is still in progress. Results of Nonlinear Time-History Analyses (NLTHA) on different configurations of BI-buildings (for the sake of brevity, not shown in this paper) confirmed the accuracy of the DDBD procedure in the attainment of the performance objective of the design (i.e. DIS = Dd and θmax = θd). The NLTHA results, however, also pointed out that some refinements to the method are still needed. Basically, they include an improved formulation of the lateral force distributions for the Linear Static Analysis of the BI-building, which should be specific for each, IS type, accounting for its actual mechanical behaviour and isolation ratio TIS/Tfb.
- Mayengbam Sunil S. and Choudhury S. [5] reported an economic comparison between a simpler form of DDBD and IS-1893 Response Spectrum method for reinforced concrete frame buildings. Buildings of two different plans, three different heights were designed with the method for the performance levels achieved from those designed by the code method and their respective costs of structural frame members are compared. The structural costs of both the categories of buildings have been evaluated. It has been found that buildings designed with direct displacement based design are more economical than those designed with the IS response spectrum method.

Critical Review

In this paper, review of relevant literature is carried out. The review of literature includes the development, implementation and comparative studies of direct displacement-based design method. Thus, this literature review defines the path for work. It also includes the advantages and limitation of the DDBD. This review helps to develop basic understanding of DDBD.

During this literature survey, it is clear that, DDBD method is a very good tool to carry out seismic design with a definite performance level. It has been implemented in many structures and comparative studies have also been defined. RC moment resisting frame design will be the focus of this study and will be compared with FBD and then the evaluation is the objective.

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Drawbacks of Forced-Based Design Method

The study of different literatures defines the drawbacks in force-based design methods.

- FBD relies on estimates of initial stiffness to determine the fundamental period of the structure and the apportioning of design base shear to different frame/ wall elements. There are disparities among design codes

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regarding the assigning of initial stiffness values for various element type to account for cracking in concrete. The New Zealand concrete design code prescribes an initial stiffness in beams based on 35% of gross section stiffness. The practice in India is to consider the gross section for both beam and columns. Accounting for stiffness degradation can result in a significant change in the estimates of design base shear and elastic drift.

- For the purpose of arriving at minimum base shear, FBD based codes generally prescribe an empirical expression for fundamental time period, which is usually a function of the height of the building and is independent of member stiffness, mass distribution and structural geometry.
- Generally low estimate of the fundamental period and it is often stated that the design is conservative and safe. The Concept of safety is questionable from the perspective of displacement demand which if calculated on the basis of an artificially low period will be low, and therefore non-conservative.
- In FBD, Design base shear is obtained by using a force- reduction factor which is based on assumed ductility capacity of the structure. However there is considerable difficulty in reaching consensus within the research community as to the appropriate definition of yield and ultimate displacements, resulting in considerable variations in the assessed ductility capacity of structure, In U.S.A., force reduction factor as high as 8 are permitted for R.C. frames. In other countries, notably Japan and Central America, maximum force reduction factor 3 and 8. This will result in a large variation in design strength.
- FBD method is unable to utilize the significant inelastic deformation capacity of the structure. Structure is designed by current design procedure when subjected to severe strong motion has been found soft storey mechanism.
- This method is more iterative and never provides good or optimal design as desired levels.

Direct Displacement-Based Design Approach

It is widely understood now that it is not the force but displacement, which can be directly related to damage. The traditional Force-Based Design (FBD) approach cannot provide the appropriate means for implementing concepts of Performance-based Design (PBD) (Bertero and Bertero, 2002). Through force-based method of design an engineer cannot deliberately design structure for an intended performance level. The alternative approaches are displacement-based design and performance-based design which are gradually becoming popular in recent times. In these methods the design is done for an intended displacement or, an intended performance under a perceived hazard level. Performance levels, indeed, are described in terms of displacements, as damage is better correlated to displacements rather than forces. As a consequence, new design approaches, based on displacements, have been recently implemented. One of such approach is the Direct Displacement-Based Design (DDBD), firstly proposed by Priestley (1993). The fundamental goal of DDBD is to obtain a structure which will reach a target displacement profile when subjected to earthquakes consistent with a given reference response spectrum.

The basis of this approach is the procedure termed “Direct Displacement Based Design” (DDBD), which was first introduced in 1993 (Priestley, 1993), and has been subjected to considerable research attention, in Europe, New Zealand, and North America in the intervening years. The fundamental philosophy behind DDBD is that structures should be designed to achieve a specified performance level, defined by strain or drift limits, under a specified level of seismic intensity. As such, we might describe the designed structures as being “uniform-risk” structures, which would be compatible with the concept of “uniform-risk” spectra, to which we currently design.

Direct displacement-based seismic design (DDBD) (Priestley, 1993, 2000) has been developed as a simple method for designing to achieve, rather than be bounded by, displacement limits that could be strain-based or code drift-limit based. The essence of the approach is to characterize the structure by the effective stiffness (ke) to the design displacement, rather than the initial stiffness (ki) , and by a level of equivalent elastic damping (xe) that represents the combined effects of elastic and hysteretic damping, rather than the 5% elastic damping normally assumed to be appropriate in force-based design.

Study Justification

The very first need that seismic design concept should move its focus from Force-based design is because FBD uses elastic stiffness which is NOT KNOWN at the start of the design. This yields towards a need of new concept. DDBD uses yield displacement or drift which is known at the start of the design. DDBD achieves a specified limit state at the design intensity; force-based design, at best, is bounded by the limit state, and vulnerability to damage is variable. The design effort with DDBD is less than with force-based design.

Conclusions

It is widely recognized that the traditional Force-Based Design (FBD) approach cannot provide the appropriate means for implementing concepts of seismic design. Performance levels, indeed, are described in terms of displacements, as damage is better correlated to displacements rather than forces. Direct Displacement-based Design (DDBD) is based on the observation, that damage is directly related to strain (structural effects) or drift (non-structural effects), and both can be integrated to obtain displacements. It has attracted considerable research into its practical advantages and shortcomings. However, less effort has been put into the study of its theoretical background and in particular the concept of equivalent viscous damping that constitutes one of its basic founding assumptions.

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