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FULL LENGTH ARTICLE

Non linear static analysis of a retrofitted reinforced concrete building

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Abstract In seismic areas many buildings need to be retrofitted. In some cases, it is possible to apply carbon fiber-reinforcement polymer/plastic (CFRP), steel-jackets, and concrete jackets as rehabilitation methods. Several researches have been developed with this technology in the last years. In addition, there are guides for the design of retrofitted systems of existing structures. However, it is necessary to count with reliable methodologies for structural analysis of these structures retrofitted. In some cases, the codes require non-linear analysis for the verification of design proposed as retrofit. In this study, an attempt has been done for investigating the seismic behavior of a typical existing building in Cairo by performing static pushover analysis before and after retrofitting the columns by either, reinforced concrete, steel sections or carbon fiber reinforced polymer (CFRP) composite jackets. The selected model building represents nearly all typical construction deficiencies of buildings constructed before recent earthquake resistant design codes. To investigate the possibility and effectiveness of the use of these systems, a comparative study was performed. A comparison was made between a typical framed RC building and the same building after retrofitting with CFRP confinement, steel elements and concrete jackets. By using nonlinear static (pushover) analysis, the performance levels of structural members were evaluated for all structures. According to the results of the structural analysis, significantly larger lateral displacement and slightly higher lateral strength with respect to original performance are possible by jacketing the columns of the building with CFRP sheets. On the other hand, a moderate larger lateral displacement and higher lateral strength by using steel-jackets was seen. In the case of reinforced concrete jacketing, the lateral strength and stiffness were significantly increased, as well as a remarkable improvement of the lateral displacement capacity.

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Introduction

Throughout the world many existing reinforced concrete structures, constructed prior to up to date earthquake resistant design procedures, suffer from the inability to supply adequate ductility during earthquakes. Particularly, brittle columns

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without adequate transverse reinforcement may cause a total collapse of this type of structure due to lack of sufficient deformation capacity. Retrofit of this type of column by means of forming an additional jacket layer may supply the required transverse reinforcement and enhance the seismic performance by providing additional ductility, and reducing the seismic force demand. In this study, the seismic behavior of a typical existing building in Cairo is investigated by using pushover analysis before and after retrofitting its columns with CFRP, reinforced concrete jackets or steel element jackets. The selected building contains most of the typical construction deficiencies that are common for the buildings constructed before recent earthquake resistant design codes. In addition to the insufficiency observed in the planning of the structural system, deficiencies such as low quality of concrete ($f'c$: 10 MPa), inadequate transverse reinforcement (12 mm diameter bars with 300 mm spacing), and usage of plain bars with relatively lower yield strength (fy: 240 MPa) also exist. Due to low concrete strength and relatively smaller column dimensions, level of axial stresses are generally greater than 50% of the axial load capacity of the sections. During the analysis of the original structure, unconfined concrete stress–strain relationship was used for determining the contribution of concrete. For the analysis of the structural members retrofitted by CFRP jacketing, a stress–strain model which was specially proposed for CFRP jacketed low strength concrete, was used. Finally, analysis of the members retrofitted by reinforced concrete jacketing or steel elements was carried out by using a trilinear confined concrete stress–strain model. Both for original and retrofitted members, a trilinear stress–strain relationship, that took the effect of strain hardening into account, was used for reinforcing steel. The analytical results showed that CFRP, steel jackets and reinforced concrete jacketing of this type of deficient column enhanced the overall structural seismic performance.

In recent years, nonlinear static analyses have received a great deal of research attention within the earthquake engineering community. Their main goal is to describe the nonlinear capacity of a structure when subject to horizontal loading with a reduced computational effort with respect to nonlinear dynamic analysis. Pushover methods are particularly indicated for assessing existing structures (Ferracuti et al.) [1].

Sonia et al. [2] checked common software SAP2000 in nonlinear analysis of retrofitting flat slab building. To analyze the retrofitting buildings methods, it is necessary to have software where the analysis of these structures can be made. Research in this area is necessary to develop and to check the accuracy of these programs.

Spoelstra and Monti [3] studied the effects of the confinement introduced by the FRP wrapping for the reinforced concrete with FRP.

Marco Savoia et al. [4] compared the results obtained from the test program and finite element analyses using two programs SAP2000 [5] and SeismoStruct [6]. The results on comparison showed that it is possible to get a good accuracy of the highest load that a RC frame can reach through the pushover analysis in SAP2000 or in Seismo Struct.

So, in this study, analyses have been performed using SAP2000 Version 15 which is a general purpose structural analysis program for static and dynamic analyses of structures.

Purpose of pushover analysis

The purpose of the pushover analysis is to evaluate the expected performance of a structural system by estimating its strength and deformation demands in designing earthquake resistant buildings by means of a static inelastic analysis, and comparing these demands to available capacities at the performance levels of interest. The evaluation is based on an assessment of important performance parameters, including global drift, inter-story drift, inelastic element deformations (either absolute or normalized with respect to a yield value), deformations between elements, and element and connection forces (for elements and connections that cannot sustain inelastic deformations). The inelastic static pushover analysis can be viewed as a method for predicting seismic force and deformation demands, which accounts in an approximate manner for the redistribution of internal forces occurring when the structure is subjected to inertia forces that no longer can be resisted within the elastic range of structural behavior. The pushover is expected to provide information on many response characteristics that cannot be obtained from an elastic static or dynamic analysis. The following are examples of such response characteristics (Helmut Krawinkler) [7]:-

- The realistic force demands on potentially brittle elements, such as axial force demands on columns, force demands on brace connections, moment demands on beam-to-column connections, shear force demands in deep reinforced concrete spandrel beams, shear force demands in unreinforced masonry wall piers, etc.
- Estimates of the deformation demands for elements that have to deform in-elastically in order to dissipate the energy imparted to the structure by ground motions.
- Consequences of the strength deterioration of individual elements on the behavior of the structural system.
- Identification of the critical regions in which the deformation demands are expected to be high and that have become the focus of thorough detailing.
- Identification of the strength discontinuities in plan or elevation that will lead to changes in the dynamic characteristics in the inelastic range.
- Estimates of the inter-story drifts that account for strength or stiffness discontinuities and that may be used to control damage and to evaluate P-delta effects.
- Verification of the completeness and adequacy of load path, considering all the elements of the structural system, all the connections, the stiff nonstructural elements of significant strength, and the foundation systems.

Background to pushover analysis

The static pushover analysis has no rigorous theoretical foundation. It is based on the assumption that the response of the structure can be related to the response of an equivalent single degree-of-freedom (SDOF) system. This implies that the response is controlled by a single mode, and that the shape of this mode remains constant throughout the time history response. Clearly, both assumptions are incorrect, but pilot studies carried out by several investigators (Lawson [8], Fajfar [9], Saiidi [10]) have indicated that these assumptions lead to