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Seismic performance of reinforced concrete columns retrofitted by various methods

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ABSTRACT

In this study, various retrofit methods for concrete columns with non-seismic reinforcement details were developed and investigated: steel jacketing, carbon fiber reinforced polymer (CFRP) wrapping, concrete jacketing with non-shrinkage mortar, and new concrete jacketing with amorphous metallic fiber (AMF) reinforced concrete. Eleven half-scale reinforced concrete columns including two different control specimens, which were designed to fail in shear or flexure-shear, and nine retrofitted specimens were fabricated and tested under cyclic loading, simulating earthquake loading combined with axial loading. Two different retrofit strategies were applied to the control specimens: partial retrofit in the plastic hinge zone, mainly aiming at increasing deformability, and full retrofit in the entire range of columns, aiming at increasing both shear strength and deformability. The seismic capacity of the test specimens was analyzed in terms of various factors: load–drift relationship, dissipated energy, damping ratio, effective stiffness, and ductility. The test results showed that the retrofitted specimens presented ductile failure mode and enhancement in the dissipated energy and the damping ratio, but the effect differed for each retrofit method. Furthermore, based on the test results, the variables (or conditions) used to define the modeling parameters of the nonlinear analysis specified in ASCE 41-13 were modified in order to use the parameters of nonlinear analysis after retrofitting the columns. In addition, the nonlinear load-deformation curves established based on the modified conditions were compared with the test results.

1. Introduction

Based on the experience of earthquakes that have occurred over the past several decades (including those in Agadir, Morocco in 1960 [1], Chile in 1960 [2], and Managua, Nicaragua in 1972 [3]), most previous concrete buildings not satisfying the special requirements of current seismic design codes have shown significant damage or entire collapse. Collapse of such reinforced concrete buildings was primarily caused by column failures, which were attributed to inadequate details (widely spaced hoops with open hooks) of transverse reinforcement and poor anchorage of longitudinal reinforcement [4].

In most developing countries, concrete buildings were designed to resist mainly gravity load. According to inspections of concrete buildings constructed before 1988 in Korea [5], the concrete columns have widely spaced hoops with a hook angle of 90°; such detail results in a lack of concrete confinement and buckling of the longitudinal reinforcing bars, thus leading to a reduction of shear capacity, flexural capacity, and subsequently deformation capacity of the columns. In addition, in the old concrete buildings, concrete with a low compressive strength (15–20 MPa) was used, which is not permitted in the current seismic design codes. When such concrete buildings are subjected to earthquake loading, the columns show drastic decrease of lateral load-carrying capacity after peak load and poor deformation ductility, not satisfying the seismic design requirement [6,7]. Therefore, existing concrete buildings and structural members need to be rehabilitated to perform reliable seismic performances as specified in the current seismic design codes.

For reinforced concrete columns having non-seismic reinforcement details, various retrofit methods and details have been developed. One of the most well-known retrofit methods is steel jacketing in plastic hinge regions to confine the concrete columns. Aboutaha and Jirsa [8] experimentally investigated the seismic performance of columns retrofitted with 6 mm thick steel jackets installed with a number of anchor bolts having a diameter of 25 mm. The test results showed that the steel jacketing method significantly improved the lateral load-carrying capacity of the concrete columns. Moreover, it was found that the steel jacketing method could not only change the brittle failure of concrete

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columns to a more ductile failure but also improve the energy dissipation capacity of the concrete columns [9,10].

In the study by Sezen and Miller [11], nine concrete columns with non-seismic reinforcement details were strengthened with 51 mm thick concrete jackets having different reinforcement details including spiral re-bars, welded wire fabric (WWF), and prestressing tendons, and were tested to investigate the seismic performance of the retrofitted columns. From the test results, it was found that the use of the concrete jacketing method could enhance the initial stiffness, strength, and deformation capacity of the columns.

Fiber reinforced polymers (FRPs) were also widely used for the retrofit of concrete columns to improve the strength and ductility of the columns [12,13]; the use of FRPs wrapping method could save considerable construction cost, while the FRPs could be easily formed into various shapes for the concrete columns. Ozcan et al. [14] tested five concrete columns, which were wrapped with CFRP sheets and fixed with CFRP anchors, to investigate the effect of confinement ratio and anchor configuration on the seismic performance of concrete columns after retrofitting under cyclic loading. The test results showed that the concrete columns were effectively confined to enhance deformation capacity and load-carrying capacity.

The recent study by Rousakis and Tourtouras [15] focused on the use of polypropylene fiber ropes (PPFRs) as external transverse reinforcement to strengthen the reinforced concrete columns. In the study, two types of PPFRs were used: a type of PPFRs was non-impregnated applied by hand as passive (loose) confinement; and the other type of PPFRs with pretension was used as active confinement. The test results showed that the columns strengthened with PPFRs increased the load capacity up to 40% compared to the one before strengthening, and the sudden load drop after peak load was mitigated.

In the study by Cho et al. [16], a new seismic retrofit method for concrete columns was developed by applying high performance fiber reinforced cementitious composites (HPFRCs) instead of concrete locally in the plastic hinge zone ranging from 450 to 600 mm. Based on the obtained test results, it was found that replacing concrete locally in the plastic hinge regions with HPFRCs could improve significantly lateral load-carrying capacity and deformation capacity, and also considerably reduce macro flexural shear cracks.

From the experimental studies mentioned above and many other studies [17–25], various seismic retrofitting and strengthening techniques applicable to existing concrete buildings have been developed. In addition, based on the test results, seismic evaluation and retrofit design provisions (e.g. ASCE 41-13 [26], NRCC 2010 [27], JPDPA 1990 [28], and Eurocode 8-1 [29]) have been established. However, some provisions are not applicable for the evaluation of concrete members after retrofit, or they do not address recent research results using retrofit techniques; for instance, in ASCE 41-13 [26], the modeling parameters which are necessary to establish nonlinear load-deformation curves are not applicable to concrete columns after retrofit.

In this study, to understand the seismic behaviors of retrofitted columns, eleven half-scale reinforced concrete column specimens were tested; two control specimens were designed to fail in flexure-shear or shear, and nine specimens were retrofitted locally in the plastic hinge or fully within the entire range of columns. Four different retrofit methods were used: steel jacketing, carbon fiber reinforced polymer (CFRP) wrapping, concrete jacketing with non-shrinkage mortar, and new concrete jacketing with amorphous metallic fiber (AMF) reinforced concrete. It should be noted that each retrofit method for the columns was performed with an emphasis on the practical details, specifically their applicability and constructability. All specimens were tested under simulated seismic loading together with axial loading. Based on the test results, the variables (or conditions) used to define the nonlinear modeling parameters of retrofitted columns were modified for the consistent use of the existing modeling parameters in nonlinear analysis, even after retrofitting of the columns, because current seismic evaluation and retrofit provisions such as ASCE 41-13 [26] do not consider the effect of retrofitting. The findings from the test results and investigation results enhanced an understanding of the seismic performance of the concrete columns with non-seismic reinforcement details and of practical techniques needed to effectively strengthen such columns.

2. Retrofit considerations

According to existing studies [30–34], the existing reinforced concrete columns subjected to seismic loading could fail in four different modes according to their flexural and shear capacities. The first possible failure mode of the columns is the shear failure before yielding of the longitudinal reinforcement that does not present sufficient deformation capacity of the columns. This failure mode is expected when the longitudinal reinforcement ratio is excessively high or the shear span to depth ratio (a/d) is very low. The second failure mode is the flexure-shear failure, where the columns exhibit a considerable deformation capacity after yielding of longitudinal re-bars but finally fail in shear as shear strength decreases with increasing nonlinear deformation. This failure mode is expected when non-seismic details of transverse reinforcement are used. The third failure mode is flexural failure, where the shear capacity of the columns is greater than the shear demand to fully exploit flexural strength. For the failure mode, seismic details of transverse reinforcement are necessary to adequately confine the concrete cross sections for ensuring concrete axial strain ductility, and to mitigate significant degradation of the shear capacity of the columns because of cyclic loading [35]. The last failure mode is the lap splice failure of the longitudinal re-bars which are frequent in beam-column connections. According to Eurocode 8-3 [36], in the concrete square columns having four corner re-bars and adequate lap splice length higher than minimum, such failure could be avoided.

In this study, two different retrofit strategies were applied to enhance the ductility and shear capacity of the two control concrete columns: one control specimen was designed to fail in shear mode before yielding of longitudinal reinforcement (first failure mode) and the other was designed to fail in flexure-shear mode after yielding of longitudinal reinforcement (second failure mode). Fig. 1 shows the seismic retrofit strategies of the columns specified in FEMA 547 [32]. The first retrofit strategy is applicable for those columns that are expected to fail in shear mode and the main intention is to increase the shear strength. In fact, in the retrofit strategies, the failure mode of columns can frequently change from shear failure to flexure-shear failure (or flexure failure) and the ductility of the columns also increase. As shown in Fig. 1a, for the first strategy, in this study, four different retrofit methods including steel jacketing, CFRPs wrapping, concrete jacketing with AMF reinforced concrete, and concrete jacketing with non-shrinkage mortar were applied for the entire range of columns. The second retrofit strategy is applicable for those columns expected to fail in flexure-shear mode, and the main intention is to increase the ductility and to change the failure mode of the columns (from flexure-shear failure to flexural failure). As shown in Fig. 1b, for the second strategy, in this study, steel jacketing and CFRPs wrapping were partially applied in the plastic hinge regions. In this study, the plastic hinge length was defined as equal to 1.5D, where D is the width of the column section. The gap between the