Engineering Structures 147 (2017) 705–723

Contents lists available at ScienceDirect

Engineering Structures

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

Improving seismic performance of old-type RC frames using NSM technique and FRP jackets

Ali Seifi [a,*], Abdollah Hosseini [a], Mohammad Sadegh Marefat [a], Mohammad Sajjad Zareian [b]

[a] School of Civil Engineering, College of Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran
[b] Department of Civil Engineering, Ferdowsi University of Mashhad, P.O. Box 91775-1111, Mashhad, Iran

ARTICLE INFO

Article history:
Received 14 March 2017
Revised 7 June 2017
Accepted 12 June 2017

Keywords:
Old-type RC frames
Smooth bar (plain bar)
Beam-column joint
Near surface mounted (NSM)
FRP jackets
Flexural strengthening
Soft storey
Seismic retrofit

ABSTRACT

Joint strengthening of the existing RC frames with smooth bars (plain bars) built before the 1970s, protects beam-column joints against shear failure and increases the lateral load resistance of these frames; but due to the inherent flexural weakness of the columns, and the lack of strong column-weak beam mechanism, the occurrence of soft storey is probable in these frames under lateral loads, thereby making them vulnerable. In order to find a suitable solution for the seismic retrofitting of these frames, different retrofit strategies were investigated. NSM technique was utilized for the flexural strengthening of columns as an effective and practicable method, and for the seismic retrofitting of joints, FRP jackets were considered due to their compatibility with the NSM technique. Consequently, by combining these techniques, different retrofit strategies were proposed. To evaluate these strategies, first the proposed physical models for columns, beams, and joints were extracted based on the experimental results, and the analytical model of the frames was created by assembling these physical models. Afterwards, nonlinear static and incremental dynamic analyses were conducted. The results indicate that in the frames with strengthened joints and columns, strong column-weak beam concept is achieved, soft storey mechanism is eliminated, and the lateral load capacity and the dissipated energy increase considerably. Therefore, the seismic performance of the frames improves. Also, the flexural strengthening of columns is adequate to be performed up to the storey in which soft storey mechanism may occur, and the flexural strengthening of the columns at other storeys does not have a major effect.

1. Introduction

In the early decades of RC buildings construction, the reinforcement detailing, e.g. the cut and bend of bars, the shape and spaces between stirrups, the details of bar splices, and the geometry of the hooks, was put into practice empirically in different countries, because there were no standards. So, in order to investigate the behavior of old-type RC buildings, the construction practice should be taken into consideration. Smooth bars were widely used to reinforce the concrete buildings in Europe, Asia, and Oceania. Due to lack of seismic provisions in the codes before the 1970s, seismic detailing is not observed in these buildings [1], and the designing of these buildings was carried out based on the gravity loads. The majority of these buildings have stiffer and stronger beams than columns and due to the lack of strong column-weak beam mechanism and the probable occurrence of soft storey mechanism, they are vulnerable under lateral loads [2]. It is, therefore, necessary that the behavior of these buildings under lateral loads be assessed and a suitable strategy for retrofitting them be proposed.

In the recent decades, some research has been done on the behavior of RC buildings with smooth bars and their components, that can be found in the literature for beams [3], columns [4–8], beam-column joints [9–13], and frames [14,15].

To resolve the problem of strong beam-weak column and seismic rehabilitation of the old-type RC frames, it is necessary that the flexural strengthening of columns and the seismic retrofitting of joints be given priority. Some methods of joints retrofitting in RC frames are joint enlargement [16,17], concrete jacket [18], beams weakening [19], FRP jacket [20–25], installing HPFRCC panel [26], and post-tensioning [27]. The concrete columns with non-seismic detailing are critical structural elements under earthquake, that various techniques have been proposed for their flexural strengthening such as concrete jacket [28], steel jacket, externally bonded reinforced (EBR) FRP strips [29], and near surface mounted (NSM) technique [30,31]. Using concrete and steel jackets is not

* Corresponding author.
E-mail addresses: aliseifi@ut.ac.ir, seifi@mohandesan.ac.ir (A. Seifi), hosseiniaby@ut.ac.ir (A. Hosseini), mmarefat@ut.ac.ir (M.S. Marefat), zareian@mail.um.ac.ir, sajjad.zareian@gmail.com (M.S. Zareian).

http://dx.doi.org/10.1016/j.engstruct.2017.06.034
0141-0296/

Nomenclature

The following symbols were used in this paper:

ϕ	diameter of smooth bar (mm)
Φ	diameter of deformed bar (mm)
h, b	height and width of the section, respectively (mm)
L	length of specimen (mm)
d_{NSM}	diameter of NSM bar (mm)
f_y	yield strength (MPa)
f_u	ultimate strength (MPa)
ε_y	yield strain (%)
ε_u	ultimate strain (%)
A_g	gross area (mm^2)
f_c	cylindrical compressive strength of concrete (MPa)
F_{max}	peak force of specimen (kN)
$F_{max,control}$	peak force of control specimen (kN)
μ	ductility ratio
Δ_y	yield displacement (mm)
Δ_u	ultimate displacement (mm)
K_i	secant stiffness per cycle (kN/mm)
F_{mi}	average peak force values per cycle (kN)
D_{mi}	average peak displacement values per cycle (mm)
F_i^+, D_i^+	peak force and displacement in positive dir. per cycle
F_i^-, D_i^-	peak force and displacement in negative dir. per cycle
DI	damage index
δ_{max}	maximum displacement during each loading step
δ_u	ultimate displacement capacity under monotonic loading
β	model parameter
Q_y	calculated yield strength
dE	incremental dissipated hysteresis energy

Abbreviations

NSM	Near Surface Mounted
FRP	Fiber-Reinforced Polymer
CFRP	Carbon Fiber-Reinforced Polymer
GFRP	Glass Fiber-Reinforced Polymer
LVDT	Linear Variable Displacement Transducer
IDA	Incremental Dynamic Analysis
PGA	Peak Ground Acceleration

practical in strengthening the columns, because of the executive problems and increasing dimensions, weight, stiffness, and earthquake demand [31]. The FRP wrapping of the RC columns with smooth bars increases the axial strength, shear strength, and ductility capacity of the columns; but it has a slight effect on the flexural capacity [28,32]. Externally bonded FRP strips can be utilized to increase the flexural capacity of the columns, but if these strips are not anchored to the base, there will be no effect [33]. One of the most suitable methods for flexural strengthening of RC columns is the NSM technique, due to ease of implementation, low-labor, no increase in the section dimensions, extension of reinforcements into the base, appropriate transfer of tensile stress from concrete to NSM reinforcements, and reduction possibility of debonding failure. The NSM technique was first proposed in Europe in the 1940s [34]; and when FRP materials and two-component adhesives became available, its usage was developed in flexural and shear strengthening of beams and flexural strengthening of slabs. This technique is carried out by cutting grooves into the concrete cover, creating holes along the grooves in the foundation or base, anchoring the reinforcement in the base, filling the grooves with bonding agents, and placing the reinforcement in the grooves [35]. If the epoxy resin is used as bonding agent, and the FRP wrapping is installed at the column ends, the efficiency of the NSM technique will heighten remarkably [31,33]. Among different NSM reinforcements, the steel bars have the advantage over FRP reinforcements in terms of ductility [31].

In the seismic zones, the retrofit of old-type RC building structures with historical and cultural importance is a top priority. This study investigates different retrofit strategies using NSM technique and FRP jackets considering technical and economic features, and a suitable seismic retrofit scheme is proposed for these buildings. To achieve this, three and five-storey existing concrete frames were modeled in OpenSees software. The columns of the frames had hooked lap splices, and the NSM technique was considered to strengthen them. Due to the lack of experimental results of the strengthened columns with hooked lap splices, four column specimens were tested under quasi-static cyclic loading and experimental results were utilized for numerical modeling of the columns. To model the beams and joints of the frames, experimental results from literature were used. Owing to the compatibility between joints strengthening with FRP materials and NSM technique, this method was adopted to strengthen the joints.

2. Experimental program and results

The columns of buildings under study have hooked lap splices. As there are no experimental results about columns with hooked lap splices strengthened using the NSM technique, an experimental phase covering four half-scale specimens was planned based on the materials and practice of the old-type RC buildings, and tested in the structural laboratory of the University of Tehran. This section presents the specifications of specimens, the method of test, and a summary of the experimental results needed for analytical modeling.

As seen in Fig. 1, the column sub-assemblages were extracted from an existing three-storey RC building built in Iran before the 1970s, which had a storey height of 5.0 m, and assuming the contraflexure point at the mid-height of the columns. The specimens included two control specimens without strengthening and with different longitudinal bar lap splices, i.e. without splices (WS) and with hooked lap splices (HS), and also two specimens strengthened using the NSM technique. The specifications of the specimens are summarized in Table 1, and dimensions and reinforcement details of the specimens are illustrated in Fig. 2. The specimen WS represented the upper half of the column (under the floor level) which lacked splices. The specimen HS represented the lower half of the column above the foundation or above the floor level which had lap splices with a length of 20 times the bar diameter. To strengthen the specimens, epoxy resin was utilized as bonding agent, and steel bars was used as NSM reinforcement because of their ductile behavior. The geometry of the grooves was based on ACI 440.2R-08 [35]. The FRP wrapping of column ends protects NSM reinforcement against premature buckling, improves capacity of NSM reinforcing, and upgrades the behavioral parameters of concrete at the end of the columns. As a result, a three-layer CFRP jacket which was 500 mm high (equal two times the height of the section), was installed at the end of the strengthened specimens. Before installing these wrappings, the sharp corners of the section got rounded and the surface of the specimen was cleaned up; afterwards, the CFRP jackets were installed with the epoxy adhesive.