Engineering Structures 150 (2017) 115–134

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental assessment and numerical modelling of exterior non-conforming beam-column joints with plain bars

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ARTICLE INFO

Article history:
Received 4 April 2017
Revised 30 June 2017
Accepted 13 July 2017

Keywords:
Unreinforced RC joints
Cyclic experimental tests
Hook-ended plain bars
Joint panel shear behaviour
Slippage of reinforcement
Numerical modelling

ABSTRACT

The seismic performance of existing Reinforced Concrete (RC) frames is significantly influenced by the behaviour of beam-column intersections, especially in non-conforming buildings with poor structural details and completely unreinforced joints. In literature, a very limited number of studies deals with specimens reinforced with plain hook-ended longitudinal bars, widespread in Italian and Mediterranean building stock, or with the analysis of local aspects, such as the experimental evaluation of joint shear strains. The almost totality of the models proposed in literature for simulating the cyclic behaviour of RC joints was developed and calibrated by means of tests performed on elements with deformed bars, and, thus, these models may be not adequate for elements with hook-ended plain bars, especially due to the peculiarities in terms of failure mode and interaction mechanisms between concrete and steel.

This study analyses the experimental cyclic behaviour of four full-scale exterior unreinforced RC beam-column joints with plain reinforcing bars in beams and columns, which differ for joint aspect ratio and beam longitudinal reinforcement ratio. First, experimental global and local responses of such tests – including energy dissipation capacity and observed damage evolution – are analysed. The main deformation mechanisms ascribable to the joint – namely rotation at the interface between beam/columns and joint, and shear deformation of the joint panel – are experimentally evaluated to provide a realistic support for the numerical modelling of this typology of beam-column joints. Then main joint shear strength models existing in codes and literature are compared with the experimental results. Finally, the numerical modelling of the specimens is carried out under monotonic loading to reproduce the envelope of the experimental responses. The joint panel constitutive parameters are defined to reproduce the experimental joint shear stress-strain relationships. Additionally, modelling of bond-slip is particularly taken into account due to the poor quality of steel-concrete interaction in the specific case of plain reinforcing bars.

1. Introduction

Past and more recent earthquakes in Italian and Mediterranean area have shown a high vulnerability of the existing building stock subjected to ground shaking ([1–3]). The overwhelming majority of the existing Reinforced Concrete (RC) buildings are “non-conforming” to the most recent and updated technical and seismic codes. The design of such buildings was often performed only for gravity loads or according to old seismic codes. In these cases, no strength hierarchy principles have been applied by the designers, so that, generally, shear failures are very likely, especially in beam-column intersections without a proper transverse reinforcement, thus limiting the achievement of the flexural capacity of the ductile elements ([4,5]).

In last decades, a significant amount of experimental studies has been performed to assess the seismic performance of unreinforced beam-column intersections ([4,6–10]). These studies often analysed the beneficial or detrimental effect of some parameters (for example column axial load, concrete strength, joint aspect ratio, or beam longitudinal reinforcement ratio) on joint shear strength. Few researchers try to experimentally assess the seismic performance of joints without stirrups in the joint core and with plain hook-ended longitudinal reinforcing bars in beams and columns, widespread in the existing RC building stock of the Mediterranean region. Some of them tested beam-column joints with a minimum amount of transverse reinforcement in the joint panel ([11–13]), or assessed the effect of axial load ratio ([11,13]) or different anchorage details ([11,13–15]) on joint shear strength and

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http://dx.doi.org/10.1016/j.engstruct.2017.07.039
0141-0296/

hysteretic dissipation capacity. Other works in literature also compared the experimental performance of interior and exterior joints with plain bars without stirrups in the joint core ([14–17]), or tested possible retrofitting strategies mainly to increase the shear strength of this joint typology (e.g. [18]). These experimental studies proved that exterior joints are more vulnerable to shear failures with respect to interior joints [17], and highlighted (i) the influence of the slippage of longitudinal bars on the response of such elements ([17,19]), and (ii) a typical failure mode that exhibits the detachment of a concrete wedge from column cover especially for exterior joints (mainly due to the stress concentration at the hook anchorage location after the shear cracking of the joint panel) [16]. Finally, four tests were performed by the authors ([20–22]) on unreinforced exterior beam-column joints, comparing the performance of joints with plain and deformed bars, and investigating about the effect of beam longitudinal reinforcement amount on joint shear strength, failure mode, and deformability contributions.

The number of tests performed on RC joints without a proper transverse reinforcement with hook-ended plain bars in beams and columns is certainly very low if compared with the amount of data available for unreinforced RC joints with deformed bars [21]. Furthermore, these few tests are generally designed and realized to reproduce different constructive practices, typical of different countries, resulting in a great inhomogeneity in terms of main features of the specimens (e.g. anchorage details, or presence of slab or of a minimum amount of ties in the joint core). Researchers often focused their attention mainly on the shear strength of the joint panel; thus, only few of them provided experimental values for joint shear strains, nevertheless the crucial role of these data to reproduce the seismic behaviour of joints through numerical modelling in a reliable way.

Furthermore, only two strength models exist in literature properly for this joint typology. The first one was proposed by Pampanin et al. [16]. On the basis of two tests on T-joints, they proposed a limitation of the traditional shear strength model adopted for joints with deformed bars [23], which appeared necessary due to the peculiarities of the observed failure mode (with the above-mentioned detachment of a concrete cover wedge). The resulting joint shear strength only depends on concrete compressive strength, not taking into account the effects of other parameters such as joint aspect ratio or longitudinal reinforcement of the adjacent members (often defined as key parameters, for example, by Park and Mosalam [25] for joints with deformed bars). The second model was more recently proposed by Metelli et al. [26], on the basis of a modification of the mechanical-based approach by Hwang and Lee [27] and a validation phase on five tests with plain bars.

1.1. Research objectives and significance

Certainly, more experimental data are necessary to assess and validate the existing models or to propose a new model for this kind of elements due to their peculiarities in failure mode and steel-concrete interaction quality. Furthermore, a complete characterization of the nonlinear local response of the joint panel and fixed-end-rotation contribution is necessary to clearly understand the joint behaviour under cyclic loading and to reliably model this element for structural analyses of non-conforming RC frames.

The work presented herein aims at extending the experimental campaign previously carried out and analysed by the authors on specimens characterized by deformed and plain longitudinal bars, in order to improve the understanding of the behaviour of exterior joints with hook-ended plain bars in non-conforming RC buildings under seismic loading. Main aims of this research are: (i) the experimental analysis of joint local shear response; (ii) the analysis of the effect of joint aspect ratio and beam longitudinal reinforcement amount on joint shear strength and deformability contributions; (iii) the evaluation of the reliability of the strength models existing in literature for this kind of structural elements reinforced with plain bars; (iv) the numerical modelling of the paramount deformability contributions for these elements (namely joint shear strains and fixed-end-rotation contribution) to reproduce the envelopes of the experimental responses.

Therefore, four experimental tests on exterior joints without transverse reinforcement with hook-ended longitudinal plain bars, different for joint aspect ratio and beam longitudinal reinforcement, are designed and tested under cyclic loading. The global experimental responses, the evolution of the observed damage, and energy dissipation capacity are shown and discussed. The main deformation mechanisms of the joint region are analysed. In particular, the shear deformability of the joint panel and the contribution of the slippage of longitudinal reinforcing bars to the overall deformability are investigated. Finally, observed shear strength values were compared with predictions provided by the main formulations proposed in codes and in literature.

Then, a numerical simulation is carried out to reproduce the experimental envelopes by means of OpenSees software. The joint panel shear response is empirically defined to reproduce the experimental joint shear stress-strain relationships. Additionally, bond-slip is particularly taken into account by introducing a slip spring whose properties are mechanically calculated using different bond-slip models, properly chosen depending on the quality of the steel-concrete interaction. The selected numerical results are finally presented and overlapped to the experimental responses.

2. Description of the experimental campaign

2.1. Test specimens and materials properties

Four full-scale exterior unreinforced beam-column subassemblages have been designed and tested under cyclic loading. All the specimens are reinforced with hook-ended plain longitudinal rebars. Columns (top and bottom) have a square cross-section with height (h_c) and width (b_c) equal to 30 cm for all the specimens (see Fig. 1). The four tests differ for joint aspect ratio (h_b/h_c) and beam longitudinal reinforcement amount (A_{sb}), in order to observe and analyse the effect of such parameters on joint shear strength and deformability, as explained in Section 1.1. In particular, beam sectional area is rectangular with 30 cm depth (b_b = 30 cm) for all the specimens; whereas the beam height (h_b) is equal to 40 cm for Tests #1bP and #2bP, and 60 cm for Tests #1cP and #2cP (Fig. 1). Thus, joint aspect ratio results to be equal to 1.33 or 2.00, respectively, depending on beam height. Column length was designed to be representative of typical interstorey height (3.40 m), so that column shear length, L_c (up to the centreline of the beam), is equal to 1.70 m. The beam length, L_b (up to the centreline of the column) is equal to 1.80 m (Fig. 1).

Beam longitudinal reinforcement is higher for Tests #1bP and #1cP (symmetrically reinforced with 4 Φ20) with respect to Tests #2bP and #2cP (symmetrically reinforced with 4 Φ16). Column longitudinal reinforcement consists of 4 Φ20 for both the reinforcement layers so that a weak beam-strong column hierarchy is obtained for all the specimens.

Joint panel is completely lacking transverse stirrups, in compliance with code prescriptions in force in the Mediterranean area at least until ’90, also in regions with high seismic hazard. On the other hand, beams and columns were transversally reinforced so that their eventual shear failures did not anticipate the shear failure of the joint panel, which is the focus of this work.

Longitudinal bars of beams are hook-ended plain bars with hooks bent within the joint panel. Hook geometry is realized