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Experimental tests of unreinforced exterior beam–column joints with plain bars

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ABSTRACT

Reinforced concrete buildings designed according to obsolete seismic codes or for gravity loads only are widespread in Italian and Mediterranean building stock. Past earthquakes showed that, for these buildings, shear failure in beam–column joints can lead to structural collapse mainly due to the inadequate joint confinement. The construction details used in these structural elements are commonly recognized as the likely cause of non-ductile structural failure modes under seismic actions, due to the lack of capacity design principles.

A significant amount of research on seismic performance of unreinforced beam–column joints has been carried out in last years, but a very few portion of them handled with specimens unreinforced in the joint region and with plain hook-ended longitudinal bars. A higher number of tests is needed to deeper understand joint seismic response in order to validate the (few) existing models or calibrate new ones.

This study aims at improving the understanding of seismic performance of exterior non-conforming joints in existing RC buildings. Two experimental tests on joints without transverse reinforcement are designed and carried out. The specimens are different for beam longitudinal reinforcement ratio and they are both reinforced with plain longitudinal bars. Two different kinds of joint failure are expected, with or without yielding of the adjacent beam. Design criteria, adopted setup and main experimental results are described. Strain gauges located on beam bars and displacement transducers on the joint panel allow the complete definition of both the deformability contributions of fixed-end-rotation and shear strain of joint panel. Finally, a comparison between joint shear strength models existing in literature or codes and experimental results (considering a wider experimental database) is carried out.

1. Introduction

Reinforced Concrete (RC) buildings designed according to obsolete seismic codes or for gravity loads only are widespread in Italian and Mediterranean building stock. For these buildings, beam–column joints can represent a critical issue, potentially leading to a shear failure that limits the deformation capacity of adjoining members [1,2].

Past earthquakes showed that shear failure in beam–column joints can lead to building collapse [3] mainly due to the inadequate joint confinement, in particular for structures designed for gravity loads only. For instance, the observation of damage after L'Aquila earthquake (2009) showed that RC buildings designed in Italy before the mid-1990s – a large part of which are reinforced with plain bars – may have serious structural deficiencies especially in joint regions, mainly due to the non-application of capacity design principles and poor reinforcement details [4], i.e. the lack of transverse reinforcement in the joint region.

A significant amount of research on seismic performance of unreinforced beam–column joints has been carried out in last years (e.g. [5–10,1,11,12]. These researches have been focused on an array of different variables, in particular including the effect of column axial load, concrete strength, joint aspect ratio, and beam longitudinal reinforcement ratio, but very few of them handled with specimens unreinforced in the joint region and with plain hook-ended longitudinal bars.

First tests on beam–column sub-assemblages with hook-ended plain bars, a minimum amount of transverse reinforcement in the joint region, and different anchorage details were carried out by Liu [13]: exterior and interior joints were tested with a single stirrup in the joint region and the effect of axial load ratio and hook details were investigated. Later, Pampanin et al. [14] performed experimental tests on six 2/3 scaled beam–column sub-assemblages,

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with structural deficiencies typical of Italian construction practice between the 50s and 70s. Two interior, two exterior tee and two knee joints, without stirrups in the joint core, were subjected to quasi-static cyclic loading at increasing levels of interstorey drift to investigate the effect of a variation in anchorage details or beam longitudinal reinforcement. Other tests on "non-compliant" joints were carried out by Chen [15] that investigated the case of a minimum amount of stirrups in the joint core and the effect of the variation of longitudinal beam reinforcement on seismic response, finally testing retrofit strategies based on a metallic haunch system. Braga et al. [16] tested internal and external RC beam–column joints built with low strength concrete and plain reinforcing bars, without hoops into the panel zone, highlighting the influence of slip of longitudinal bars on the response of such elements and the higher vulnerability to shear collapse of exterior joints compared to interior joints. In Bedirhanoglu et al. [17], two series of tests on exterior beam–column joints with low strength concrete and plain bars were performed. In the first series of tests, the longitudinal reinforcement of the beam was anchored in the joint with 90-degree hooks. In the second series, hooks of top bars were welded to hooks of bottom bars. Parameters varied in this campaign include axial load, amount of joint reinforcement, and displacement history. Akguzel and Pampanin [18] tested four as-built exterior beam–column joint sub-assemblages with different axial load ratio, investigating the adoption of externally bonded glass fiber-reinforced polymer (GFRP) sheets as a retrofit strategy. In Genesio [19] two tests were characterized by the use of plain bars terminating with 180°-hooks in the joint region. The test specimens had similar anchorage of beam longitudinal bars in the joint region, but different beam longitudinal reinforcement. Fernandes et al. [20] and [21] tested five interior and five exterior full-scale beam–column joints with different detailing characteristics and reinforced with plain bars, highlighting that the bond-slip mechanism significantly influenced the cyclic response of this kind of beam–column joints [22], which also showed lower energy dissipation, stiffness and equivalent damping with respect to the corresponding test with deformed bars. More recently, also in Beschi et al. [23], the RC test units were designed with structural deficiencies typical of the Italian construction practice of the 1970s: use of plain bars, lack of stirrups in the joint panel, and hook-ended anchorage.

Despite a certain amount of recent experimental tests, as listed above, the number of tests performed on RC joints built with plain bars is reduced when compared with the available data for RC joints with deformed bars [24]. Moreover, there is a great inhomogeneity (e.g. for anchorage details, presence of slab or ties in the joint core) in test campaigns carried out all around the world and representing different constructive practices typical of each country. In most of these tests, researchers focused their attention mainly on the shear strength of the joint panel, and only few of them have measured joint shear strain (e.g., Genesio [19] for unreinforced joints or Chen [15] for reinforced joints). However, a complete characterization of the nonlinear local response of the joint panel and fixed-end-rotation contribution is necessary to clearly understand beam–column joint behaviour and to model this element into structural models of non-conforming RC frames.

This study aims at improving the understanding of seismic performance of non-conforming exterior joints in existing RC buildings, extending the experimental campaign carried out and analysed previously by the Authors on specimens characterized by deformed longitudinal bars [12], and also analysing the joint local response and the reliability of the strength models existing in literature for this kind of structural elements. Two experimental tests on external joints without transverse reinforcement with hook-ended longitudinal plain bars, different for failure typology, are designed and tested under cyclic loading. The global experimental response and the evolution of observed damage are presented. The main deformation mechanisms of the RC joint region are discussed; in particular, local shear stress-strain response of joint panel and longitudinal bars slippage contributions to the overall deformability are investigated.

The tests presented herein can provide a useful contribution to enhance the quite poor database of experimental tests, briefly listed above, related to external joints without transverse reinforcement with hook-ended longitudinal plain bars. Finally, on the basis of the collected database, a comparison between joint shear strength models existing in literature or codes and experimental results is carried out.

2. Experimental program and setup

Two full-scale exterior unreinforced beam–column joint sub-assemblages have been tested under cyclic loading, see Fig. 1.

The two tests are identical for geometry. The beam is 50 cm depth (h_b = 50 cm) and 30 cm width (b_b = 30 cm). Columns (top and bottom) have a square sectional area with height (h_c) equal to 30 cm. Column length was designed to be representative of typical interstorey height (3.40 m), and column shear length (L_c) is equal to 1.45 m. The beam length (up to the centerline of the column) is equal to 1.80 m, and its shear length is L_b = 1.65 m.

As shown in Fig. 1, in Test #1P the beam is symmetrically reinforced with 4Φ20 bars for both reinforcement layers (corresponding to a compression and tension reinforcement ratio equal to $\rho' = \rho = 0.84\%$); the column is symmetrically reinforced with 4Φ20 bars for top and bottom sides, corresponding to a total reinforcement ratio ($\rho' + \rho$) equal to 2.79%. In Test #2P, the beam is symmetrically reinforced with 4Φ14 bars for both the positive and negative (corresponding to a compression and tension reinforcement ratio equal to $\rho' = \rho = 0.41\%$), and the column is reinforced with 4Φ14 bars for top and bottom sides, corresponding to a total reinforcement ratio ($\rho' + \rho$) equal to 1.37%. In both cases, top and bottom beam longitudinal bars are anchored with end hooks bent inside the joint core. The internal curvature radius of hooks is equal to 3 times the bar diameter (according to the Italian constructive practice in force until 70s), namely equal to 60 mm for Test #1P and 42 mm for Test #2P.

The transverse reinforcement consists of 8 mm diameter stirrups closed with 90° hooks, 10 cm long at both ends. The stirrups are spaced at 10 cm along the beam and the column, except within 62 cm of beam' and columns end where the spacing is reduced to 5 cm to give adequate strength at the location where forces are applied during the test. The longitudinal reinforcement in the column extends continuously up through the joint from the bottom to the top of the column.

Geometry and longitudinal reinforcement amount in beam and columns are defined by means of a simulated design procedure [25] of a perimeter 4 storey-5 bay frame according to code prescriptions and design practices in force in Italy between 1950s and 1970s. In particular, the analysed specimens are intended to be representative of external joints of the first floor of such a frame. The specimen named Test #1P is related to a frame designed according to seismic prescriptions (for medium-high seismicity level), in compliance with the Italian codes [26,27]. The specimen named Test #2P is related to a frame designed for gravity loads only.

Beam longitudinal reinforcement ($A_{s,b}$) is defined on the basis of flexural demand obtained from the simulated design. The ratio between bottom and top longitudinal reinforcement areas provided by the simulated design is approximately 3:4; however, it is slightly modified in order to assume a symmetric beam longitudinal reinforcement, as usually adopted in literature (as shown later in