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Experimental study of repaired RC columns subjected to uniaxial and biaxial horizontal loading and variable axial load with longitudinal reinforcement welded steel bars solutions

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ABSTRACT

The study of the reinforced concrete (RC) columns' response to horizontal cyclic loads is of full importance to understand how earthquakes affect the integrity of structures. Essentially those already built and especially vulnerable to this type of action, as is the case of many existing buildings on significant seismic activity zones which are not adequately prepared for that eventuality. Consequently, there is also the need to perform a significant number of studies of repairing procedures of structural elements, so as to restore its function and possibly achieve an improvement in relation to its original seismic resistance. The present experimental work is focused in the study of welding joints for steel bars used in building columns, supported by tensile tests on specimens according to the actual welding regulations. The experimental results are analyzed and discussed with particular attention to the specimens' behaviour in terms of strength and ductility compared to the results obtained for original steel bars. After the definition of the proper welding solution, six RC columns previously tested were repaired and retrofitted with this solution tested under uniaxial and biaxial horizontal loading and variable axial load in order to compare the global result with the original tested columns and the effects introduced by the repair process.

1. Introduction

The study of the reinforced concrete (RC) columns' response to horizontal cyclic loads is essential to understand how earthquakes affect the integrity of structures, essentially those already built and especially vulnerable to this type of action, as is the case with many existing buildings on significant seismic activity zones which are not adequately prepared for that eventuality [1–3].

The importance of this topic is justified by several points, namely the biaxial cyclic bending demand applied to a RC column tends to reduce its capacity and to increase the stiffness and strength degradation during cyclic loads. In RC buildings this effect is objective due to the random biaxial earthquake actions is strongly related and due to the three-dimensional building behaviour that can lead to important biaxial demands due to the effects of the structural irregularities [4–7]. Due to these effects the corner columns tends to be the most prone to biaxial bending demands, and also subjected to higher levels of axial load variation. Bearing in mind these aspects and considering the lack of experimental results on columns tested with repaired system, highlights the importance of the present study.

The variation in the axial load during an earthquake can change the strength, stiffness, and ultimate displacement, as well as all the hysteretic properties of an RC element [4]. Such variations can occur due to the vertical component of the seismic load, or in the external columns of the bottom storeys of RC frames, due to the overturning moments [5,8]. In fact, different authors have concluded that the variation in the axial load combined with the horizontal cycle actions affect significantly the inelastic response of the columns [9–11]. Only a limited number of RC columns were tested under bi-directional horizontal forces, due to testing difficulties. These columns are mainly tested under constant axial load. The lack of results do not allow researcher to take strong conclusions to be drawn about coupling behaviour between biaxial bending and the varying axial force [11–13].

Past and Recent earthquakes as the L'Aquila (Italy) in 2009 [14], Lorca (Spain) in 2011 [15], Ghorka (Nepal) in 2015 [16,17], Cental Italy in 2016 [18] revealed some problems related with the insufficient capacity of these RC elements, especially in the corner columns. Many structures exhibit deficient confinement due to inadequate transversal reinforcement, leading to brittle collapses of the compressed columns. Adequate detailing can improve the structure seismic behaviour by

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increasing their strength and ductility. Many of this structures can be repaired and retrofitted after the earthquake.

Consequently, there is the need to perform experimental studies concerning the repair of damaged RC elements after an earthquake in order to restore its capacity and possibly to achieve an improved seismic behaviour [19–22]. One possible repair strategy is the re-establishment of the longitudinal reinforcement through the execution of welded joints. However, the cyclic behaviour of welded steel bars, to be applied in RC columns, was not studied in detail according to the literature. In this way, the first part of the present work is focused on the study of welding joints steel bars solutions that can be adopted for repair or rehabilitation of building's columns. An experimental campaign of tensile strength tests (monotonic and cyclic) of four different solutions designed according to BS EN ISO 17660-1:2006 [23]. The experimental results are presented and discussed with particular attention on the specimens' behaviour and in terms of strength and ductility.

The second part of the present work is devoted to the study of the repair of previously damaged RC columns with the defined welding solution and compare the results with the original columns. Finally, the effects introduced by the repair process are analysed and discussed, through the observation of damage evolution, hysteretic behaviour, stiffness degradation and dissipated energy.

2. Welding of steel rods for repairing procedures of RC columns previously damaged

2.1. Introduction and objectives

Due to the reduced number of experimental data available in the literature for validation of repair procedures for damaged RC columns through the welding of steel rods, the existing codes such as the Eurocode 8 [24] do not consider this type of procedure for repairing RC structural elements in seismic zones.

Thus, the present study aims to evaluate the efficiency of different strategies for execution of welding of steel rods destined for repair of damaged RC columns. To accomplish this objective, it was conducted an experimental campaign of monotonic and cyclic tensile tests of four different welding of steel rods solutions, designed according to BS EN ISO 17660-1:2006 [23]. The main test results, specifications and conclusions will be presented along the present section.

2.2. Design and definition of the welding solutions

For the present study it was intended to apply the recommendations given by BS EN ISO 17660-1:2006 [23] for the design of different welded steel rods samples configurations and compare their performance under (monotonic and cyclic) tensile strength tests with those of simple steel rods.

BS EN ISO 17660-1:2006 [23] proposes four different welded steel rods configurations, namely: (a) butt joint welding (b) unilateral lap joint welding (ST1) (c) unilateral lap joint welding (ST2) and (d) Bilateral strap joint welding, which are illustrated in Fig. 1. Where *E* represents the existing steel rods that are connected to the emended *P* (but joint) and to the unilateral and bilateral steel rods welded.

According to Riva et al. [25] the tensile cyclic behaviour of the butt joint (Fig. 1a) configuration is not satisfactory, and this solution can be applicable only simultaneously applied with the unilateral lap joint welding (Fig. 1b) or the strap bilateral welding (Fig. 1d) configurations. The strap bilateral welding configuration (Fig. 1d) was also not considered in the present study since it is leads to an unnecessary increase of the reinforcement steel area, when compared with the initial one.

For the present study it was decided to evaluate the performance of the two remaining configurations ST1 and ST2 under tensile monotonic and cyclic tests. The main difference between these two configurations is the ensure of the continuity of the alignment of the existing steel rods with the elements E1 and E2 in the configuration ST1. It was intended also to observe the effects of the force deviation associated to the eccentricity observed in the ST2 samples under tensile tests. For both configurations it was created two different variants (A and B), namely variation A which corresponds to a central span length between the splicing's of 5∅ and 10∅ for variation B. The main purpose of considering these two different variations was to achieve larger height distribution for the plastic hinge in existing RC columns.

The execution of the samples were realized according the recommendations indicated in ISO 17660-1:2006 [23], such for the butt welding execution as illustrated in Fig. 2a, such for the unilateral lap joint welding execution, where the ISO 17660-1:2006 [23] recommends for the overlap of two steel rods of diameter ∅, the minimum welding length 4∅ that could be reduced for 2.5∅, for case of the welding is performed in both two sides. Where *1* (Fig. 2b) represents weld, *a* the throat thickness, ∅ nominal diameter of the thinner of the two welded bars, l_o overall lap length and *w* the weld width.

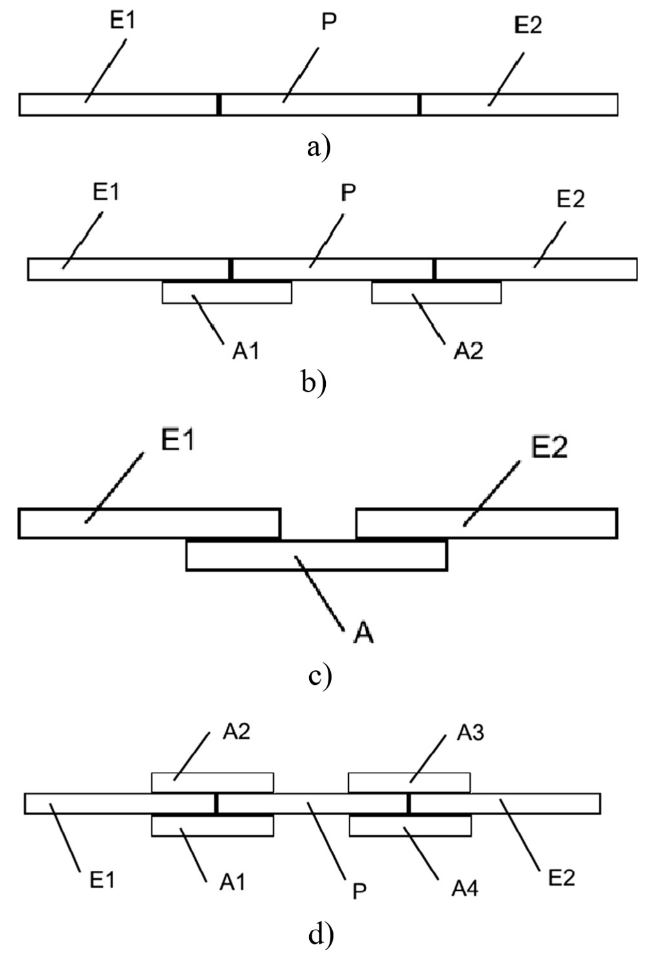

Fig. 1. Tensile test specimen configuration for (a) butt joint welding; (b) unilateral lap joint welding (type 1); (c) unilateral lap joint welding (type 2) and (d) bilateral strap joint welding.

2.3. Steel and electrodes mechanical properties

Forty-five samples were built for the present experimental campaign and it was selected a steel class S500 and the nominal mechanical values are summarized in Table 1, according to the Eurocode 2 [26]. It was used an electrode model OK 46.00 from the brand ESAB, which corresponds to the class 38 0 RC 11 according to BS EN ISO 2560:2005 [27]. The mechanical properties are summarized in Table 2, and the

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