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Experimental tests on retrofitted RC beam-column joints underdesigned to seismic loads. General approach

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ABSTRACT

This paper presents an experimental program designed to determine the behaviour of steel jacketing used as a seismic strengthening system for reinforced concrete frame structures. Tests were carried out on a total of 20 full scale interior beam-column joints. Geometry and reinforcements were selected according to existing buildings, designed solely to gravity loads under strong beam-weak column concept. Column strengthening was performed in all specimens, and four different types of column-joint connection strengthening have been tested. Two types of beam reinforcement have been included in the experimental program. Tests were carried out by subjecting specimens to gravity and cyclic loads. The paper shows general results and conclusions, describing the failure modes of the specimens. Results show that the strengthening techniques and the axial loads applied on columns can have significant influence on the seismic behaviour of the joints.

1. Introduction

In order to ensure that reinforced concrete structures show good behaviour under seismic loads, the structural components must have a certain degree of ductility. As this concept was only introduced into building standards in the 1970s, buildings erected before that time are not usually equipped to deal with earthquakes. This has been made manifest on numerous occasions in earthquakes such as those occurring in Northrige in 1994, Kobe 1995, Izmit 1999, Taiwan 1999, Bingol 2003, Sumatra 2004, Sichuan 2008 and ĹAquila in 2009.

A number of research groups [1–7] have studied the most commonly found causes of the failure of reinforced concrete structures under seismic loads. These include: soft stories, short columns, strong beam-weak column and deficient building practices, among others. However, the principal cause of building collapse is critical damage to columns and beam-column joints.

Retrofitting structures against seismic loads has now become a relatively common operation. A considerable amount is already known about how to strengthen isolated elements like beams and columns by means of different techniques; however the treatment of the beam-column joint is a more complicated task, due to the high concentration of loads on a relatively small area difficult to access in existing buildings.

At the present time several research groups in different parts of the world are studying the behaviour of the beam-column joint elements in reinforced concrete frame structures in order to improve its response to seismic loads. It is also advisable to submit existing underdesigned buildings to a study on seismic resistance to avoid structural damage during earth movements. The following section deals with a review of the state of the art of the research at present being carried out on this structural element.

1.1. Background: tests and strengthening pattern

The earliest studies on the behaviour of beam-column joints in RC structures under seismic loads were carried out in the 1960s and focused on the joint in isolation [8–11]. This meant the joint could be deformed without the restraints it would have had as part of a complete structure. During the 1990s, experiments began to include other structural elements, such as columns, beams and the beam-column joint [12].

All the research carried out to date can be divided into three main groups. The first deals with failures in joints subjected to cyclic loads designed to withstand gravity loads only [13,14]. These studies did not consider strengthening the joints but they did throw light on how they work, the deficiencies in present-day buildings and the key points that must be taken into account when designing this structural element. The second group focuses on solutions that improve the seismic behaviour of joints in new buildings and carry out tests on new arrangements for strengthening the joint core [15,16] and also on the use of special concretes [17]. The third group is involved with joints in existing buildings that are strengthened with the idea of improving their behaviour under seismic loads and can be roughly divided into two

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sub-groups. In some cases the strengthening is added before the tests [18–20] and in others the original element is first tested before being strengthened and re-tested [21–23] to evaluate the results of the strengthening.

There are three main techniques for strengthening RC columns: concrete covers [24,25], FRP composite materials [26–29] and steel jacketing [30,31]. According to [32], the strengthening technique that has received most attention in the literature is the use of composite materials and most of the recently published papers deal with this type [33,34]. However, in practice the most commonly used strengthening technique is by steel strips and angles (a variety of steel jacketing), which, as [35] point out, is fully effective in increasing the strength and ductility of RC columns.

Steel jacketing has been widely used in many European countries. For example, in the Czech Republic the technique had been used more than 5000 times up to the year 2000 [36]. It was also generally applied in Greece after the earthquake disaster in Kalamata in 1986 [35], in Japan to retrofit RC columns that had been affected by earth movements [24] and in Mexico to repair buildings after an earthquake in 1985 [37]. The CEB-FIB Bulletin No. 24 [38] analyzed the different strengthening techniques for RC columns in high seismic risk areas and classified the steel angles and strips method as being among the most suitable.

According to the American Concrete Institute [39], when structural columns are being strengthened, one of the most important aspects is the treatment of the beam-column joint. Different studies have been carried out on this method of strengthening columns [31,32,36,40–42] but very few on the behaviour of the beam-column joint in structures with steel strengthened columns subjected to cyclic loads [43].

1.2. Research objectives and significance

The main objective of this research is to determine the seismic behaviour of strengthened interior beam-column joints in RC frame structures originally designed solely to withstand gravity loads, therefore lacking in ductile details. The paper considers strengthening by steel jacketing on columns, and all the beam-column joint retrofitting have been designed in order to achieve that they are easy to fit to existing structures, as in general, access to these zones tends to be difficult.

One of the main novelties of the paper is the way how cyclic loads are applied and their combination with gravity loads in such a way that the forces applied to the specimens are as near as possible to the real forces they would experience as part of a complete structure.

2. Experimental program

Many variables with a strong influence on the final response of the specimen can be included in a test like the one described here: consideration/non-consideration of gravity loads both in beams and columns, level of gravity load, loading protocol, number of cycles, increments of loading between cycles, loading speed, force-control or displacement control, type and number of specimens and reinforcement, symmetry of the reinforcement, strengthening technique, data acquisition, data points, etc.

The variables included were intended to cover a wide range of cases. A high number of specimens were tested as compared to other studies, since specific goals were pursued with different strengthening techniques in order to acquire as much practical information as possible.

References and comments to other studies are given with the aim of a positive review of the experimental procedure here described, since much valuable information was learnt from reading previous experiences. The key points of these references are highlighted and were taken into account in the design of the experiments described in the following subsections.

2.1. Details of specimens

2.1.1. Geometry

It is well known that when properly retrofitting a column in an underdesigned beam-column structure under horizontal loads, the failure usually shifts to the joint as the next weakest part. With the aim of studying the joint, the specimens represent a common interior beam-column joint in framed buildings with strong beams and weak columns. The columns are strengthened according to [31], so that the joint core and its interfaces with beams and columns become the next weakest parts. According to this, one of the first decisions to take was on the number and scale of the specimens.

Previous investigations [40–43] have shown the influence of the capital in the joint under monotonic load. Here, two tests (plain specimens without joint strengthening, A.W. specimens) were planned as reference tests to compare against the joint strengthening technique using only capitals (A.C. specimens). The latter were used as reference tests to compare against the strengthened specimens (all including capitals) and to study the behaviour of the joint under cyclic loads. Three other strengthening techniques (apart from the use of capitals only) were desired to be tested, either because the authors had experience with them or because they wanted to find the most efficient under earthquake loads. As two axial load levels, two types of beam reinforcement and at least two specimens for each technique were involved to allow for errors or accidents, an initial total of 19 specimens were planned. The success (each of the two matching specimens in the tests had similar behaviour) and experience acquired from the tests led to a minor change in this sequence. One of the A.VB.L1 test was not carried out and was tested as A.C.L1, so that two capital-only specimens were tested (with and without axial gravity load in the column). The failed specimen was then repaired and retrofitted with vertical bars and re-tested, so a second A.VB.L1 test was performed and re-labelled A.VB.L1-R, which gave a total of 20 tests, as seen in Table 1.

The specimens geometry is based on the dimensions of seismically underdesigned real buildings from past decades, and is similar to other studies as shown in Table 2, except [17,18] that conducted scaled tests. This is done using the points of contra flexure, which are approximately at mid span of the beams and columns in all the referenced studies. The points of contra flexure are clear in the interior columns and are located at mid-height when horizontal loads are acting on the structure. However, these points are not clear in the beams if the gravity load is considered, since gravity loads lead to contra flexure points located between one fourth and one fifth of the span, while they are at mid spans for horizontal loads. The variation in the position depends on the ratio between gravity and horizontal loads. Authors like [13,17,29], among others, assume the points of contra-flexure to be located at the mid-height of columns in two successive stories and the centre-points of beams in two adjacent bays, since gravity loads are not considered.

The present study considers the effect of gravity loads on the response of the frame to seismic loads, so that the experiments were designed in this way. Since the location of zero points is load-dependent, a compromise was reached by adopting a length between one half and one fifth of the span, avoiding the D-region close to the joint and adjusting the ends of the specimen so that the jacks could be attached to ground. Some authors [19,22,47] also consider gravity loads in their experiments, but no reference is made to this fact in the geometry of the specimens. Although this is not a major point, the authors are unaware of any information on this matter in the literature.