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New connection between reinforced concrete building frames and concentric braces: Shaking table tests

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ABSTRACT

Concentric steel braces and brace-type dampers are often applied to the upgrading of reinforced concrete frames subjected to lateral loads. These braces may develop high axial tension forces, and transferring them appropriately to the existing beam–column joints is a key challenge. This paper investigates a solution for connecting the end-plate of the steel brace with the frame, using (1) shear-key plates fixed to the concrete with anchor bolts, and (2) a low friction material inserted between the end-plates and the shear-key plates. The presence of the low friction material impedes the development of tension forces in the anchor bolts and ensures that they are basically subjected to shear forces. This prevents brittle types of failure (concrete cone failure, pull-out/pry-out failure), and results in a reduction of the number of anchors required as well as anchorage height. The efficiency and validity of the proposed brace–frame connection is investigated experimentally by means of shaking table tests conducted on a $3 \times 3 \times 3$ m^3 scaled reinforced concrete frame retrofitted with brace-type hysteretic dampers.

1. Introduction

A high proportion of the building stock located in earthquake-prone regions—including the Mediterranean area—was designed before the appearance of seismic codes or in view of rudimentary anti-seismic design criteria [1]. Recent earthquakes (L'Aquila 2009, Lorca 2011) have revealed the poor performance of this type of under-designed building, accentuating the need for seismic assessment and retrofitting [2]. Many damaged buildings had reinforced concrete frames as the main system of lateral resistance; in such cases retrofitting may involve installing concentric steel braces, either ordinary ones or brace-type dampers. The former solution is very common, but the latter provides for better seismic performance. A number of brace-type dampers are commercially available or under development. Among them, the so-called "hysteretic" dampers are particularly popular because of their low cost in comparison with viscous fluid dampers or viscoelastic solid dampers. In the past two decades, the use of brace-type hysteretic dampers for the seismic upgrading of existing frames has increased exponentially. When retrofitting reinforced concrete frames with concentric steel braces, the connection between the ends of the steel braces and the existing frame (briefly referred to as "brace–frame connection" herein) is a key challenge [3]. The steel brace may develop high axial loads, and its influence on a possibly damaged frame is a matter of major concern.

Several solutions have been proposed for the brace–frame connection in the past. The simplest one consists of using steel anchors to connect the end-plate of the brace directly to the concrete, as shown in Fig. 1a. The anchors are thereby subjected to shear V_i and tension forces N_i. A second proposal [4,5] is to use shear-key plates to fasten the end-plate of the brace, as shown schematically in Fig. 1b. The shear-key plate is adhered to the surface of the concrete with epoxy resin and fixed with anchor bolts. In this second solution, there is a direct metal-to-metal contact between the end-plate of the brace and the shear-key plate. When the brace is in tension, the direct metal-to-metal contact induces forces perpendicular to the plane of the shear-key plate (denoted by V_c in Fig. 1b) that tend to uplift and detach it from the concrete surface. Because these contact forces also induce large tension forces N_i in the anchors and bending moments in the shear-key plates, there is a need for thicker plates or the addition of stiffeners. Sustaining high tension forces with bolts anchored in the concrete calls for considerable anchoring height and a greater number of anchors. Hence, this solution can prove costly or technically unfeasible. In addition, the typical failure modes exhibited by anchor bolts subjected to tension loads (concrete cone failure, pull-out/pry-out failure) are brittle.

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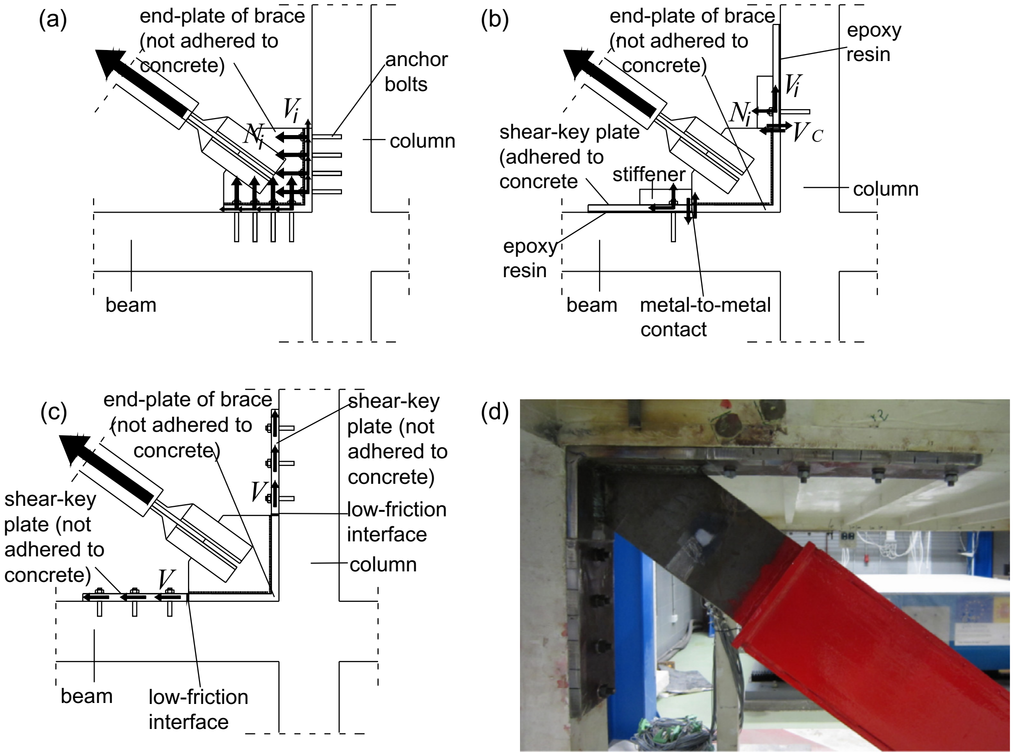

Fig. 1. Existing (a, b), and proposed (c, d) solutions for brace–frame connections.

This paper investigates an alternative solution for the brace–frame connection that improves upon the one shown in Fig. 1b, reducing the number and anchorage height of the anchors and the dimensions of the shear-key plates. The proposed solution aims to minimize or cancel the tension forces N_i acting on the anchor bolts, and the subsequent bending moments developed on the shear-key plates. The proposed brace–frame connection is suitable for connecting either a conventional concentric steel brace or a brace-type hysteretic damper. The validity and efficiency of the new connection is assessed through shaking table tests conducted on a one-story one-bay frame structure. Shaking table tests can capture the strain-rate effects associated with dynamic loading, as well as the cumulative damage to the anchoring system caused by the successive cycles of deformation that take place in structures actually subjected to seismic motions. Past research has shown [6] that strain rates anticipated in earthquake excitation (about 0.3 mm/mm × s) produce the following effects: (i) a conspicuous enhancement of the yield stress of steel materials (about 13%), and (ii) an increase of the flexural resistance of members (by 7–20%) in comparison with the strength under static loading.

2. Proposed brace–frame connection: execution provisions and design criteria

Fig. 1c and d illustrates the proposed brace–frame connection. It consists of two shear-key plates fixed to the concrete only with anchor bolts (i.e. without epoxy resin), plus a device for reducing the friction between the end-plates and the shear-key plates. This device forms a low friction interface intended to minimize the contact forces (denoted with V_c in Fig. 1b), the subsequent tension forces N_i on the anchor bolts, and the bending moments on the shear-key plates. The device consists of two sheets of polytetrafluoroethylene (simply Teflon hereafter), or else one sheet of Teflon in contact with a stainless steel surface polished to mirror finish (i.e. with less than 0.1 μm surface roughness). Past experimental investigations [7] have shown that the friction coefficient μ_c of this type of device decreases along with an increase in the contact pressure. For contact pressures of about 25 MPa, μ_c is between 0.03 and 0.1. This range of μ_c can be further reduced to about 0.01–0.02 if the interface is lubricated. By limiting μ_c, the proposed brace–frame connection ensures that the anchors are basically subjected to shear forces.

Using anchors subjected basically to shear loads makes the proposed solution (Fig. 1c) less demanding than the conventional ones (Fig. 1a and b) in terms of the number and effective anchorage depth h_{ef} of the anchors, as explained next. The guidelines for metal anchors in concrete—ETAG001 (Annex C) [8] in Europe, for example—distinguish several modes of failure and provide equations for estimating the resistance limited by each one of them. The following failure modes are considered for anchors subjected to tension loads: (i) steel failure; (ii) pull-out failure; (iii) concrete cone failure; and (iv) splitting failure. For anchors subjected to shear loads, the failure modes are: (i) steel failure; (ii) concrete pry-out failure; and (iii) concrete edge failure. According to the above-mentioned guidelines, the resistance of an anchor governed by steel failure depends on the anchor cross-section A_s and on the steel's ultimate tensile strength f_{uk}, and it is two times larger under tension loads than under shear loads. For the proposed brace–frame connection the failure of the steel is not a concern, however, because f_{uk} and A_s can be made large enough to prevent this mode of failure. The splitting failure under tension loads and the concrete edge failure under shear loads can also be avoided by using appropriate edge distances for the shear-key plates. The failure modes of concern with the proposed brace–frame connection would be those that depend on the concrete compression strength f_{ck}: pull-out failure and concrete cone failure under tension loads, and concrete pry-out failure under shear loads. For these failure modes the resistance of an anchor subjected to shear loads is twice that of an anchor subjected to tension loads. In addition, minimizing the contact forces V_c (see Fig. 1b) makes it possible to use thinner shear-key plates without stiffeners. Since the proposed