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Seismic retrofit of RC building structures with Buckling Restrained Braces

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ABSTRACT

The search for passive control systems has increased in some high seismicity areas of the world, especially in terms of the strengthening of existing RC or steel building structures designed without earthquake-resistance considerations (pre-code structures) or with outdated structural codes. One of the most promising techniques consists of adding steel Buckling Restrained Braces (BRBs) to the existing structure. This paper presents an applicability study of these devices in the retrofit of a typical existing RC pre-code school building structure. The effectiveness of the retrofit solution, initially designed according to Kasai et al. (1998) formulation, was assessed through non-linear static and dynamic numerical analyses. The results of these analyses, led to the design method being developed with the purpose of optimising the dimensions of the steel dampers at different storeys and therefore improving the structural performance. This development is based on a simplified method of predicting the response of a passive system, by devising a single degree of freedom system. The effectiveness of the seismic retrofit solution designed through the improved design procedure was confirmed, showing that the studied strengthening solution results in a significant increase in strength, deformation and energy dissipation capacity, thereby limiting damage in the original structure to admissible levels.

1. Introduction

For the past four decades, the research on modern technology for seismic damage mitigation, such as base isolation and other passive control systems has been a major issue around the world, notably in Japan. After the 1995 Hyogo-Ken Nanbu earthquake, which led to numerous building collapses and costly structural repairs in the city of Kobe, modern seismic protection systems quickly grew to replace conventional structural solutions. The pursuit of innovative seismic protection solutions and their acceptance has also increased in other high seismicity countries and regions such as the USA and Italy.

The awareness of the consequences of major seismic events around the world has resulted in a growing concern about the structural safety of both new and old structures. Given the impossibility of analysing and intervening on all the structures simultaneously, it is essential to establish priorities for large-scale seismic assessment and retrofitting. In this context, public buildings (such as state school buildings) assume a particular importance.

The need to update the school building stock of state secondary schools in mainland Portugal led to the creation of state-run enterprise named Parque Escolar. One of its functions is to assess the level of structural safety of existing school buildings, their compliance with current building codes and the need for retrofit interventions. One of the schools chosen for structural retrofitting is presented as a case study in this paper. The school, Escola Secundária Poeta António Aleixo, is in Portimão, which is a city with one of the highest seismicity levels in mainland Portugal (actual reference return period of 475 years, peak ground acceleration on type A, rock or rock-like, ground of 2.5 m/s^2) [1]. The school structure was designed in the mid-1950s, prior to the enforcement of the first Portuguese seismic design code (1958).

1.1. Buckling Restrained Braces

Buckling Restrained Braces (BRBs) have proved to be beneficial in providing resistance against horizontal earthquake ground motions while simultaneously enhancing the energy dissipation capacity of both new and existing steel structures. However, their applicability and effectiveness in RC framed structures is still uncertain. A relatively large number of different types of BRBs have been studied, tested and proposed in the past few decades. Regardless of detailing differences, they all share the same concept: to

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prevent both global and local (cross-section) buckling in the braces and allow equal tensile and compressive strength, and thus higher hysteretic energy dissipation.

The use of BRBs overcomes the typical disadvantages of normal braces, i.e. the asymmetrical hysteretic behaviour in tension and compression and the substantial strength deterioration when cyclically loaded.

The most common configuration of a BRB (Fig. 1) consists in a steel profile encased in a circular or rectangular hollow section steel profile, filled with concrete or mortar. The main purpose of the concrete-filled tube is to prevent the buckling of the steel core (that entirely sustains the axial force). The steel core-concrete interface usually consists of a slip surface to allow relative axial deformations between the steel core and the tube infill. The slip surface is achieved by placing a low friction material between the infill material and the steel core. The transversal expansion of the brace under compressive loads due to Poisson's effect should be accommodated providing a gap between the brace and the encasing material. In addition, the dissipative part of the brace, which is the zone where yielding occurs, can be replaced by detaching it from the brace non-yielding segment, which is retained (e.g., in the aftermath of a major seismic event).

1.2. Codes and regulations

In Japan, BRBs are regarded as dampers and, therefore, are regarded as a type of passive control system or scheme for seismic damage mitigation [2].

According to Kasai [3], BRBs became a viable means of enhancing the seismic performance of buildings with the publication of the JSCA Specifications in December 2000 and the publication of the JSSI Manual in October 2003. More than fifty university researchers, structural designers and engineers from about twenty damper manufacturing companies were involved in developing the JSSI Manual. It refers to the various aspects of passive control schemes, such as the damper mechanism, design, fabrication, testing, quality control and analytical modelling, as well as the analysis, design and construction of passively controlled buildings.

In the USA, BRBs have been code regulated since the release of NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 450-1) in 2003 [4]. This document provides specific rules for BRBs and other structural elements of steel BRB frames, as well as qualifying cyclic tests. As mentioned in [4], the document's recommendations for BRBs should be used in conjunction with AISC Seismic Provisions for Structural Steel Buildings [5], even though this version of AISC Seismic Provisions did not include any specific provisions regarding BRBs. It was not until 2005 that AISC Seismic incorporated, in a later version, provisions for the use of BRBs in steel buildings [6]. However, at the time, no provisions were issued for BRBs in composite steel concrete or reinforced concrete buildings. In Europe, seismic design codes omit the design of BRBs. However, despite omitting design and detailing provisions, some codes allow for the use of such devices in seismic protection. In Italy, the most recent normative environment is embodied in the NTC'08 [7], comparable to the former OPCM3431/05 [8] and in its predecessor OPCM3274/03 [9]. The NTC'08 allows for the use of anti-seismic dissipative devices (e.g., braces) in both new and existing structures, setting forth general design rules and providing for other relevant indications (e.g., compliance tests and installation, maintenance and replacement related requirements). Moreover, in 2009 the European Committee for Standardisation (CEN) issued the European Standard EN15129 [10], which contains provisions for performance requirements, materials and testing of displacement dependent devices, besides other seismic devices such as velocity dependent devices and isolators.

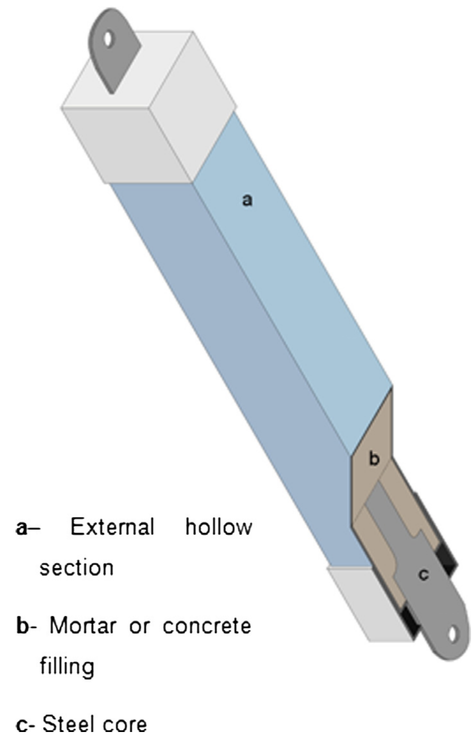

Fig. 1. Traditional BRB configuration.

As a preliminary conclusion one could state that the use of BRBs for new steel buildings is reasonably framed by codes and regulations, contrarily to what happens in their use in reinforced concrete (or composite) buildings. This remark becomes even more critical in the retrofit of old, pre-code or low-code, reinforced concrete buildings, where the stable energy-dissipation capabilities of BRBs could provide for a promising retrofitting solution (as long as the specificities of these structures, such as low ductility and deformation capacity, are properly considered).

2. Review of BRB design procedure

Given the nonlinear nature of its dynamic behaviour, the BRB design should be based on nonlinear dynamic analysis. On the other hand, the absence of specific design provisions for BRB use in retrofitting RC structures indicates that known preliminary design methods, should be adopted, such as those used for hysteretic steel dampers in steel frames (henceforth simply referred to as dampers). For the purpose of our work, the design method formulated by Kasai et al. [11] was used. This method is based on devising a single degree of freedom (SDOF) system that has the same vibration period as the multiple degree of freedom (MDOF) of the structure under assessment.

With the exception of the BRBs, which are assumed to have elastoplastic behaviour, the existing structure should remain in the elastic domain for the whole duration of the seismic ground motion. The objective of this premise is that all potential seismic damage (plastic deformations) is concentrated in the BRBs.

Fig. 2 illustrates the SDOF model devised for a structure with added hysteretic damper elements. This model is composed of two sets of springs in parallel, together with another spring placed in series, connected to a mass M. The set consisting of two springs placed in series is called sub-system "a". Sub-system "a" represents the brace-damper assembly added to the framed structure, in which K_b is the brace non-yielding segment (non-dissipative part of the BRB) stiffness, K_d is the damper (dissipative part of the