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Numerical investigations of repairable dissipative bolted fuses for earthquake resistant composite steel frames

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ABSTRACT

This study presents the main results of the numerical investigations carried out on an innovative repairable fuse device for dissipative beam-to-column connections in moment-resisting composite steel frames. The fuse consists of steel plates bolted to the web and bottom flange of the beam with a specifically detailed gap in the concrete slab. The behavior of the fuse device is studied by means of two different numerical approaches. Numerical analyses performed on detailed three-dimensional finite element models of beam-to-column sub-assemblages show that potential damage concentrates only in the fuse section, without any significant damage in the other structural elements. Repair work, if needed, is therefore limited to the replacement of the fuses only. The effects of some geometrical characteristics of the flange plates on the behavior of the fuses are investigated. In order to extend the results of the numerical analyses to multi-storey frames subjected to seismic excitations, simple numerical models of the device are developed and calibrated through the experimental results of laboratory tests. Non-linear dynamic and static analyses are performed on multi-storey composite steel frames and the effectiveness of the fuse devices is evaluated. The influence of the main mechanical characteristics of the different devices on the seismic performance of several composite steel frames is also discussed for various ground motion intensity levels. Experimental and numerical results show that it is possible to successfully dissipate energy and concentrate plasticity by means of the fuse system, along with simple and cost effective repairability.

1. Introduction

Modern seismic codes allow for significant plastic deformations in dissipative zones of building structures under design seismic actions, provided that the integrity of both individual members and the structure as a whole is not endangered. The design seismic loads are considerably reduced, as compared to elastic design, for building structures designed for energy dissipation and ductility. This design philosophy results in increasing concerns with the repairability of structures damaged by severe earthquakes.

As regards steel buildings, the large number of beam-to-column connection failures observed in moment-resisting frames in past earthquakes caused very high repair costs. New design approaches have been proposed for moment-resisting frame connections, implementing solutions that aim at shifting the plastic hinge and the associated large plastic deformations into the beams, away from the potentially brittle beam-to-column connection welds. The reduced beam section (RBS) connection [1] is an option for improving the ductility of steel beam-to-column connections in high seismicity regions. This solution has been extensively studied and is able to concentrate plasticity and provide energy dissipation, as shown, among the others, in [2]: nevertheless, the repair of the beam damaged by severe earthquakes presents serious practical difficulties. Simple and cost-effective repairability of the damaged parts of the beam represents a crucial issue and a challenging research item. Therefore, new design approaches are intended to develop devices that can simultaneously dissipate energy through the non-linear behavior of their components and be easily repaired.

The majority of past experimental and numerical research on dissipative and easy-replaceable fuses has been devoted mainly to steel braced frame structures and significant developments have been achieved. Dubina et al. [3] investigated eccentrically braced frames with removable links connected to the beams using flush end-plate bolted connections. High-strength steel was used for members outside links in order to enhance the global seismic performance of the structure by constraining plastic deformations to removable links and reducing permanent drifts of the structure. Mansour et al. [4] presented an experimental research program

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to develop and assess the design of replaceable links for eccentric braced frames. The test program included cyclic tests on both individual link specimens and full-scale eccentrically braced frame sub-assemblages. Tan and Christopoulos [5] presented the development of replaceable cast steel links for eccentric braced frames that integrate the advantages of replaceable yielding links with the benefits of steel castings to achieve large ductility. Two types of replaceable link configurations with alternate link-to-beam connections were tested. Plumier et al. [6] developed innovative dissipative systems for concentric braced frames, comprising pinned and "U" type connections: the application of such innovative systems to concentric bracings in steel frames and to other types of structures is shown in [7,8]. Chan et al. [9] conducted an experimental study on a metallic passive energy dissipative device that utilizes plastic shear deformation of diaphragm steel plate. Giannuzzi et al. [10] proposed an innovative seismic-resistant steel framing system capable of providing stiffness and ductility to new or existing structures. The bracing system consists of concentric X-braces connected in series with rectangular sacrificial shear panels. The braces are designed to remain elastic during seismic events, while the shear panels are sized and configured to dissipate energy through stable hysteretic behavior.

Focusing on moment resisting frames, Koetaka et al. [11] presented a novel beam-to-column moment connection suitable for the column weak axis: a wide-flange beam was joined to a wide-flange column by bolted splices at the top flange and hysteretic dampers at the bottom flange. Oh et al. [12] developed a repairable beam-to-column connection system with a slit damper connected to the bottom flange of the beam using high-strength bolts. Balut and Gioncu [13] suggested two replaceable "dog-bone" solutions for moment-resisting frames: the dissipative element could be an I-beam with end plates or two channels bolted to the beam. Shen et al. [14] conducted combined analytical and large-scale experimental studies to validate two types of replaceable link with different bolted connections. Vargas and Bruneau [15] investigated a design approach to concentrate damage on removable structural elements, with the main structure designed to remain elastic or with minor inelastic deformations.

This study is part of the "Fuseis" project that aims at developing innovative types of seismic-resistant composite steel frames with dissipative fuses. The devices are made by introducing a discontinuity in the composite beams of a moment-resisting frame and assembling the two parts of the beam through steel plates bolted or welded to the web and flange of the beam. Within the "Fuseis" project, experimental tests on beam-to-column specimens and frame sub-assemblages equipped with fuse systems were carried out at Instituto Superior Tècnico (IST) of Lisbon and at Politecnico di Milano: bolted and welded fuse device solutions were experimentally tested and the main results are reported in [16–19].

The work described in this paper presents the main results of the numerical investigations conducted on the bolted fuse devices shown in Fig. 1. The behavior of the bolted fuse devices and the effects on the seismic performance of composite steel frames are analyzed through two different numerical approaches. First, the refined finite element modeling technique, for which the computational effort is very heavy, is used to develop detailed three-dimensional finite element (FE) models of beam-to-column sub-assemblages with fuse devices by means of the computer code ABAQUS [20]. Numerical analyses are conducted in order to have a better understanding of the response of the connections equipped with the device and to demonstrate that the whole plasticization occurs in the fuses only. The effects of different geometric properties of the flange plate, such as thickness, cross section area and free buckling length, on the response of the fuse are also investigated and comparisons with the results of the experimental tests are made. Moreover, the refined three-dimensional FE models are used to obtain some mechanical characteristics (elastic stiffness and moment resistance capacity under sagging and hogging rotations) of fuses that were not tested during the experimental campaign.

Then, simple numerical models are developed by means of the commercial software SAP2000 [21] in order to investigate the seismic response of multi-storey composite steel frames. After the calibration of the numerical models according to the results of experimental tests, non-linear dynamic and static analyses are carried out on different types of steel frames with fuse devices, in order to simulate more realistic cases and evaluate both the response of the fuses and the global behavior of the structures. The seismic performance of multi-storey frames with and without fuse devices is compared for various ground motion intensity levels in terms of top displacement, base shear, plastic energy dissipation, residual drift and damage distribution.

2. Experimental tests

Within the "Fuseis" research project, two types of experimental tests were carried out in order to assess the performance of the fuse devices under cyclic actions. The laboratory tests performed at Instituto Superior Tècnico of Lisbon were aimed at characterizing the behavior of the device in terms of moment-rotation curves. Then, a portion of a full-scale composite steel frame with fuse devices was tested at Politecnico di Milano in order to simulate a real scale case.

2.1. Laboratory tests at Instituto Superior Tècnico of Lisbon

The experimental test set-up and the beam-to-column sub-assemblage with the fuse device configuration used in the laboratory tests at Instituto Superior Tècnico of Lisbon are shown in Fig. 2. To assess the performance of the fuse device, experimental tests were conducted on different sub-assemblages of beam-to-column joints, imposing cyclic displacements at the free edge of the beam by means of an actuator. The proposed devices proved to be very easy to replace and were able to both concentrate plastic deformations in the steel plates and dissipate large amounts of energy through stable cyclic behavior. A detailed description of the specimens and the results of the extensive experimental campaign carried out at Instituto Superior Tècnico of Lisbon can be found in [17]. The longitudinal reinforcement of the 150 mm thick concrete slab consisted of $\phi 20/100$, top layer, and $\phi 16/100 + \phi 12/200$, bottom layer (dimensions in mm). Full shear connection was provided between the slab and the steel beam by means of IPE100 sections (spacing = 150 mm) welded on the top of the beam flange, acting as shear studs. A pair of reinforcing plates ($230 \times 300 \times 6$ mm) were welded to the beam web near the fuse device and a pair of transverse beams (HEB200 profile) were placed in the column web at the beam-to-column joint. High strength friction grip (HSFG) bolts (size M16, class 8.8) were used to connect the steel plates to the beam in the fuse region. The bolts were tightened according to provisions given in EN 14399 [30] (minimum preload equal to 88 kN and coefficient of friction between the different surfaces equal to 0.2).

2.2. Laboratory tests at Politecnico di Milano

The experimental test set-up represents a portion of a storey of a composite steel frame, as shown in Fig. 3. The bases of the columns were restrained against horizontal and vertical displacements through pin connections and cyclic displacements were imposed at the top of the columns by means of an actuator. Full shear connection was provided between the slab and the steel