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Hysteretic behaviour of dissipative bolted fuses for earthquake resistant steel frames

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Highlights

- A new fuse device for moment resistant steel frames was developed.
- The behaviour of these devices was studied through experimental tests.
- Fuses present good energy dissipation capabilities and are also easy to repair.
- The proposed design models show good agreement with experimental data.

Abstract

One of the most recent trends in earthquake-resistant design of structures – damage control when these are subjected to severe earthquakes – led to the development of an innovative repairable fuse device for dissipative beam-to-column connections in moment resistant steel frames with composite beams. This fuse consists of a set of bolted steel plates, at the web and bottom flange, connecting the "I" beam profile stub to the beam element. The seismic performance of the proposed device was assessed through an extensive experimental campaign comprising twenty-four cyclic and two monotonic tests. Those tests were conducted on a set of three beam-to-column sub-assemblies with different fuse devices for each test. The tested devices varied in terms of selected geometric and mechanical parameters, such as the resistance capacity ratio and the geometric slenderness. The tests showed that the proposed devices were able to concentrate plasticity and to dissipate large amounts of energy through non-linear behaviour. Subsequently, two distinct design models are proposed to allow the computation of the resistance and stiffness of the fuses. The results of these design models were favourably compared with those from the experimental tests.

Introduction

Some of the seismic events that have occurred in areas with significant concentration of steel structures, such as Northridge (USA, 1994) and Kobe (Japan, 1995), led to widespread failure of a large number of beam-to-column connections in moment-resisting steel frames (Engelhardt and Sabol [1]), in turn, leading to unexpectedly high repair costs. These and other unanticipated consequences of severe earthquakes have led to an increased concern over the repair ease and cost, raising the awareness over the need for new, more stringent, design requirements that go beyond collapse prevention. These emerging design requirements can be considered to fit in the broader requirements of economy and sustainability of modern construction.

Considering the specific case of earthquake resistant steel frames, new design approaches have been implemented 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, thus avoiding the detrimental effects in both energy dissipation and ductility due to local storey mechanisms. Amongst the preferred solutions are those that introduce weakened areas near the beam ends; these are able to concentrate plasticity and develop large deformations and, thus, force of the plastic hinge to occur within certain limits (Mazzolani [2]).

One of the first solutions of this type was the reduced beam section (RBS), introduced by Plumier [3]. This solution, despite being able to successfully dissipate energy and concentrate plasticity, as shown experimentally (Pachoumis et al. [4]; Yu and Uang [5]), presented difficulties in terms of the repairability of damaged parts of the structure. New solutions point towards devices that can simultaneously dissipate energy through non-linear behaviour of their components and be easily repaired. Significant developments have been achieved in research on dissipative and easy-replaceable fuses for eccentrically braced frames (EBF), concentrically braced frames (CBF) and knee braced frames (KBF). Chan et al. [6], Li and Li [7] and Bruneau et al. [8] conducted experimental tests on EBF systems with different link geometries. Plumier et al. [9] developed innovative dissipative systems for CBF that comprised pinned and "U" type connections. The dissipative capacities of KBF systems were studied by Hsu and Chou [10], who performed cyclic experimental tests on a frame with different knee brace geometries.

Focusing on moment resisting frames (MRF), experimental cyclic tests have been widely used to investigate the dissipative capacities of traditional bolted or welded moment connections (Dubina et al. [11]; Adany et al. [12]; Mele et al. [13]). Koetaka et al. [14] proposed alternative weld-free moment connections between composite steel-concrete beams and the weak axis of the column. These connections are made through replaceable steel plates bolted to the upper and bottom flanges of the beam. Oh et al. [15] developed an innovative fuse based on a damper system fitted at the bottom flange of the beam at the beam-to-column connection.

The aforementioned scenario motivated the FUSEIS research project, that aims at the development of innovative fuse devices for moment-resisting steel frames, with the following functional objectives: devices that are easy to design and manufacture; high seismic performance and low-cost repair work. Given these objectives, preliminary numerical investigations were undertaken by Mazza and Pedrazzoli [16], which concluded with the optimal fuse configurations, resulting in one bolted and one welded solution. The behaviour of the welded fuse alternative was assessed experimentally and numerically by Calado et al. [17] and Espinha [18]. The work described in this paper focuses on the experimental investigations on the bolted fuse alternative.

Section snippets

Fuse specimens

The basic test assembly consisted of a typical beam-to-column sub-assembly, comprising a composite beam with an IPE300 profile supporting a 150mm thick and 1450mm wide reinforced concrete slab, with a HEB240 profile column, as shown in Fig. 1.

The fuse device studied consists of steel plates bolted to the web and bottom flange of the beam with M16, together with a specifically detailed slab gap, as schematically shown in Fig. 1. Non-linear behaviour is expected to concentrate only in the fuse…

Overall hysteretic behaviour

The analysis of the results was mainly based on the moment-rotation diagrams in the fuse (M-θ). As an example, the M-θ diagrams for both tests on fuse C-170 are shown in Fig. 3.

The diagrams show that the hysteretic behaviour of the fuses is stable, characterised by a marked pinching phenomenon, due to the slippage of the bolts and to the buckling of the fuse plates when under hogging. The latter phenomenon also explains the asymmetry of the diagram in terms of moments, due to the strength loss…

Development of design models and comparison of results

The experimental results were further used to derive and validate commensurate design models with which some of the behaviour characteristics of the fuses could be accurately predicted. The validation of the proposed design models was performed comparing the resistance and stiffness results, in which the material properties used in the design models' expressions were those obtained experimentally through tensile tests conducted for that purpose.…

Conclusions

The developed bolted fuses proved to be very easy to replace and showed good performance indicators in terms of ductility, stiffness, energy dissipation and resistance. The fuses successfully protected the majority of the irreplaceable parts, which generally remained in the elastic domain as intended, which was achieved by concentrating the inelastic behaviour in the fuse plates. These fuses also proved to be easy to manufacture, to assemble and to replace.

Experiments have shown that the…

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