INNOVATIVE SYSTEMS FOR SEISMIC RESISTANCE
The INNOSEIS Project

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ABSTRACT

Following the international trends, extensive research on seismic resistant structures has been carried out in Europe during the last decade, with the introduction of several systems with innovative steel-based elements, as the result of European and national research projects. However, these systems have not claimed a fair share of the steel construction market, as provisions for their design have not been included in the Eurocodes and only a few designers are confident enough to employ them. The INNOSEIS project, which has received funding from the Research Fund for Coal and Steel (RFCS) with the participation of 11 partners, aims to deal with this shortcoming. In this paper, the valorisation actions for 12 such innovative anti-seismic devices are presented. Information documents for all dissipative systems have been produced and combined in a single volume, translated in several European languages, for the dissemination to all partners of the construction sector such as architects, structural engineers, construction companies, steel producers and all potential decision makers of the construction sector. Criteria are proposed as to determine which of the systems are characterised as devices and are subject to CE marking in accordance with EN 15129, and which may be considered as innovative systems that require a code approval in EN 1998-1. For the latter, pre-normative design recommendations are drafted that will allow them to receive the status of code-approved systems. A reliability-based methodological procedure to define values of behaviour factors (q-factors) for building structures is proposed, which will be in turn applied to determine q-factors for structural systems with the anticipated systems. A number of case studies with application examples of realistic steel buildings, in which the systems are employed, are presented. Dissemination of the project includes seminars and workshops in several European and Mediterranean countries, as well as the development of online, printed and electronic material, which is free for all people involved in the construction sector, in order to achieve the wide application of innovative seismic resistance systems in practical design.

Keywords: seismic resistance, dissipative systems, design, dissemination

1 INTRODUCTION

Seismic analysis and design for buildings is governed in Europe by the provisions of EN 1998-1 [1]. The number of code-approved structural systems in EN 1998-1 is limited to a few conventional systems. Indeed, for steel buildings the code covers actually only four original lateral-load resisting systems, namely moment-resisting frames, concentric or eccentric braced frames and concrete cores or walls, while it reports on moment-resisting frames in dual action with braced frames or infill walls. The list is identical for composite steel-concrete buildings, with the addition of composite shear walls composed of steel plates encased on one or both sides with reinforced concrete. For these systems, information on modelling, analysis, design and structural detailing are provided, including values of the behaviour q-factors to be used when linear analysis methods are employed.
Besides EN 1998, the European Standard EN 15129 [2] co-exists by regulating anti-seismic devices that are produced on an industrial basis and covered by relevant patents. These devices are installed in buildings, bridges or other types of structures in order to protect the structural elements in the event of an earthquake. They modify the seismic response of the structure by isolating it, by

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dissipating energy or creating restraints through a rigid connection. EN 15129 covers the design of these devices by providing general design rules, specifying material characteristics, manufacturing and testing requirements, as well as installation and maintenance criteria.
Seismic activity with intensity well above the one prescribed by the codes was observed worldwide in the last decades. Extensive damage up to structural collapse has been reported that affected mostly old but also new buildings from all structural materials. The reputation of steel or composite buildings as the most appropriate construction type in seismic areas was compromised by the fact that significant damage appeared in new buildings of technologically advanced countries like US (Northridge 1994), Japan (Kobe 1995) or New Zealand (2011). As a consequence, significant research has been carried out to better understand and improve the seismic behaviour of building structures subjected to earthquakes. Innovative structural and anti-seismic systems have been developed and implemented in practice. In parallel, seismic Codes were extended to include new lateral-load resisting systems. The US seismic code for example includes today more than 80 individual structural systems.
Following the international needs, extensive research on seismic resistant structures has been carried out in Europe. In the last decade, a number of systems with innovative steel-based dissipative systems have been invented as the result of national and European research projects. In all cases, innovative elements were introduced that are able to dissipate energy during strong seismic motions and accordingly protect the main structure from inelastic action and damage.
Two categories of systems are examined in the project. Type 1 systems are exclusively made of steel parts that undergo inelastic deformations and are possibly damaged when subjected to cyclic loading. These systems contain pins, thin plates or short beams of small dimensions and are designed to act as fuses that may be easily dismantled and replaced if damaged after ground motion of intensity equal to or higher than the design earthquake. The fuse elements are not covered by patents and may be produced freely. Similarly to the tension diagonals of an X-braced frame, they constitute structural parts that dissipate energy and modify the structural response but do not require a CE marking in accordance with EN 15129. Innovative structural systems in which these elements are employed could be included as code-approved systems in a new version of EN 1998-1, provided specific analysis and design methods and other important parameters, like behaviour q-factors, are established. The Type 2 category comprises displacement- or velocity-dependent devices that provide energy dissipation and damping. They are produced by specific manufacturers and have received a CE marking in accordance with EN 15129 that specifies the tests to be carried out to determine the device properties and manufacture control. These devices are not intended to act as fuses, having instead a continuous presence within the structure and meant to survive multiple events. However, they are subjected to inspection at regular time intervals and after every major seismic event, with the possibility of replacement.
The target of the INNOSEIS project is twofold: (a) to disseminate knowledge on 12 innovative systems in order to reach a wider use in practical application, and (b) to offer the tools for formally promoting any new lateral-load resisting system to a code-approved status via a standardized performance-based methodology to determine reliable behaviour factors. Thus, the project enhances the seismic safety of buildings, widens the application of steel-based solutions, increases the number of code-approved systems and reduces the life-cycle cost of structures, enhancing sustainability. Six interdependent actions are envisaged as following:

- Collect information and produce documentation for 12 innovative systems.
- Draw the limits between two European Standards on structures with dissipative systems.
- Develop and edit pre-normative design guidelines for these systems.
- Establish a procedure to determine consistent behaviour factors to be used in linear design methods.
- Apply the guidelines in case studies to document the design approach and validate the behaviour factors.
- Organize seminars and workshops to disseminate the knowledge within EU and internationally.

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2 DESCRIPTION OF SYSTEMS FOR SEISMIC RESISTANT BUILDINGS

2.1 INERD pin and U connections

INERD pin and U connections were developed during the RFCS-supported INERD project [3-5]. The connections are composed of a steel pin or a U-shaped steel plate and connect the ends of braces in concentric braced frames (Fig. 1). INERD pins transfer brace axial forces through three-point bending, while U-plates bend and roll along the column face. The connections act as semi-rigid ductile dissipative brace connections. The connections are of partial strength in order to protect the braces from yielding and buckling, so that energy dissipation occurs exclusively within them and not in the braces. They can easily be replaced if damaged after a strong seismic event. The connections and the overall frames were experimentally/analytically/numerically studied at NTUA Athens, POLIMI Milano and IST Lisbon.

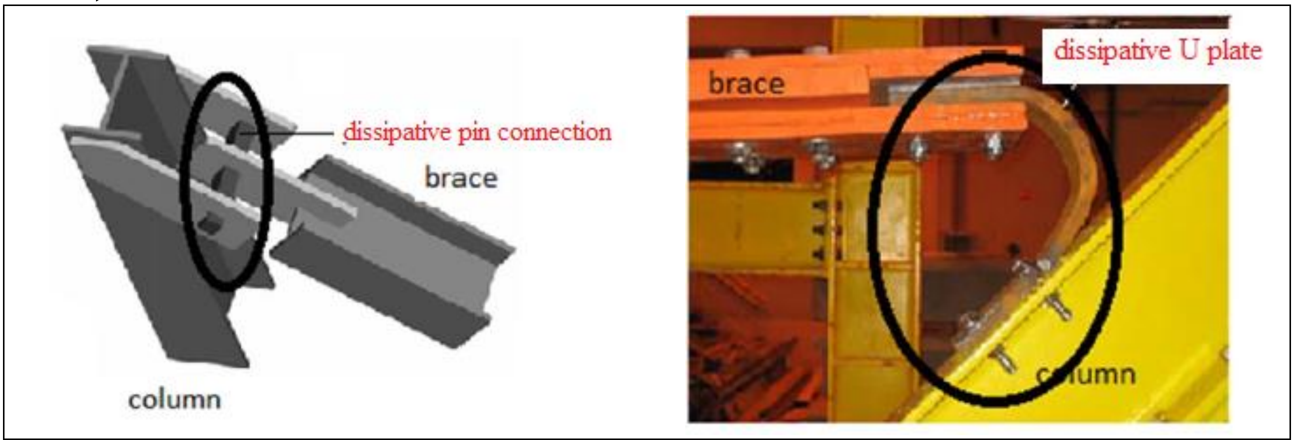

Fig. 1. INERD pin and U connections in concentric braced frames

2.2 FUSEIS beam and pin links

FUSEIS beam and pin links were developed during the RFCS-supported FUSEIS project [6-9]. Multiple links connect within a storey's height to closely spaced strong columns (Fig. 2). The system responds to seismic loading similar to a vertical Vierendeel beam, where the links are subjected to bending and shear. Beam links may be of open or closed section and have reduced sections near their ends, while section reduction for pin links is around their middle. The links and the overall frames were developed and experimentally/analytically/numerically studied at NTUA Athens and RWTH Aachen.

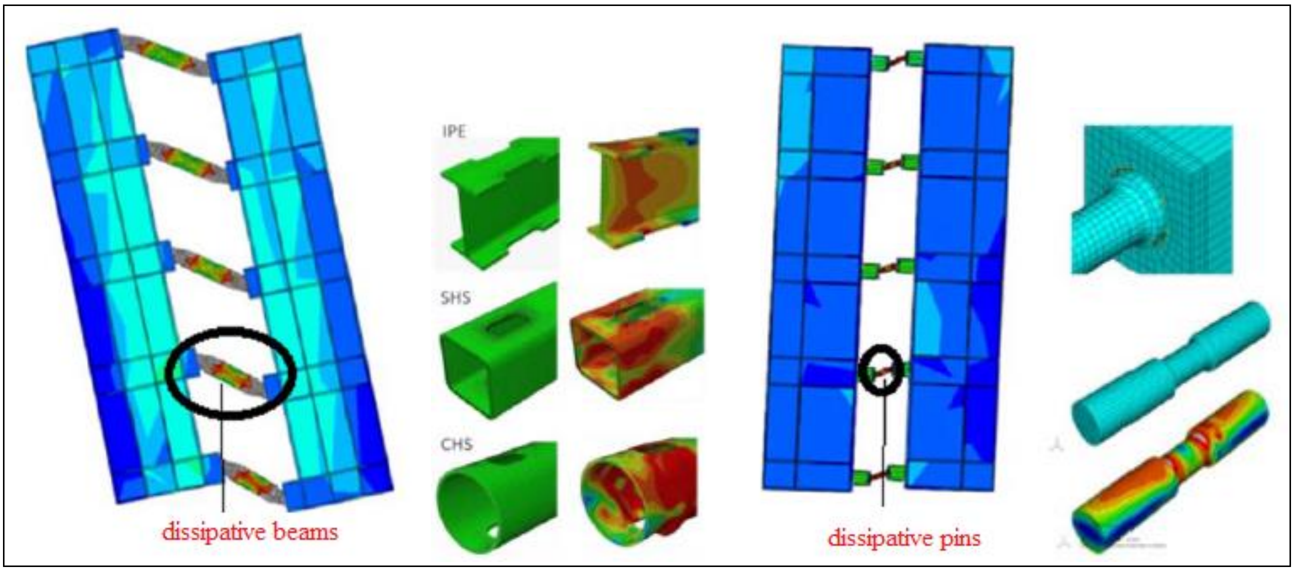

Fig. 2. FUSEIS beam and pin links

2.3 FUSEIS bolted and welded beam splices

These splices were also developed during the RFCS-supported FUSEIS project [10-12]. They may be employed in moment resisting composite frames, where the beam sections act compositely with the concrete slab. The continuity of the beams is interrupted and then restored by steel cover plates that connect the web and the lower flange of the beams (Fig. 3). The steel cover plates may be bolted or welded to the beam. The cross section at the beam splice is weaker so that energy dissipation and damage concentrate on the cover plates which can be easily and quickly replaced. The splices were developed and investigated both experimentally and analytically at POLIMI Milano and IST Lisbon.

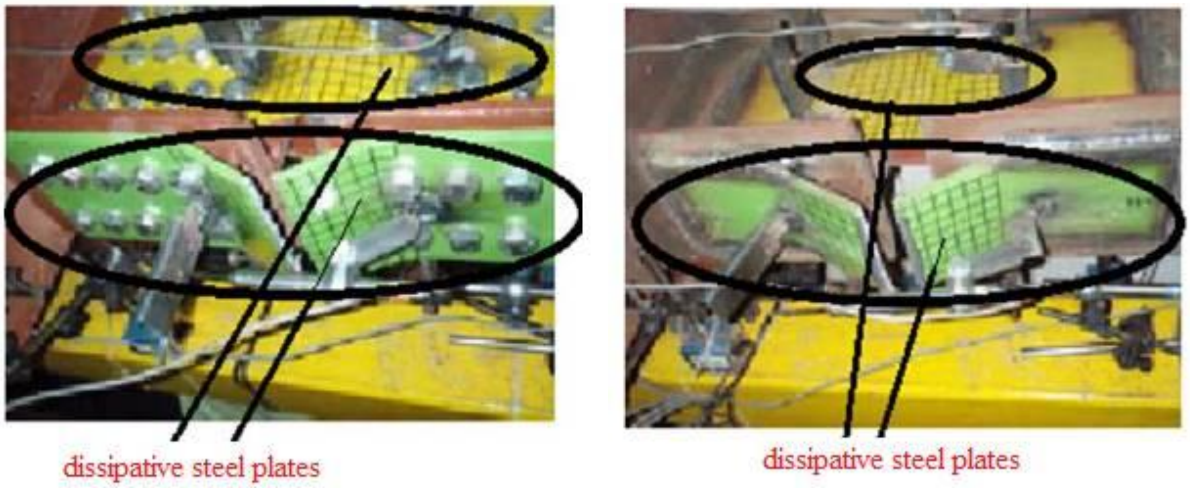

Fig. 3. FUSEIS bolted and welded beam splices

2.4 DUAREM replaceable bolted link

DUAREM replaceable bolted link was developed and studied experimentally and analytically by UPT Timisoara in a Romanian research project. Additional experimental tests were performed at the ELSA Laboratory at JRC Ispra during a European FP7 SERIES project [13-15]. The system consists of short links that are bolted to the floor beams in eccentric braced frames (Fig. 4). They are employed in dual frames consisting of moment resisting frames and eccentric braced frames. The design is such that energy dissipation concentrates at the links which can be removed when damaged. The moment resisting frame acts as a second line of defence that provides the potential for re-centring (straightening) after the seismic event.

Fig. 4. Large-scale testing of the DUAREM system at JRC Ispra

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2.5 SPSW replaceable thin-walled shear panel

Steel-plate shear wall panels consist of a thin steel plate that is bolted to a surrounding strong steel frame (Fig. 5). By placing more such panels vertically along the building height, a shear wall system is composed. The dissipative element of this system is the steel plate that is subjected to high shear and develops tension fields in opposite directions as the seismic forces change sign. The connection and the frame are capacity-designed so that damage concentrates in the steel plate that can be easily removed. The shear panels were developed and experimentally/analytically studied by UPT Timisoara during a national Romanian research project [16].

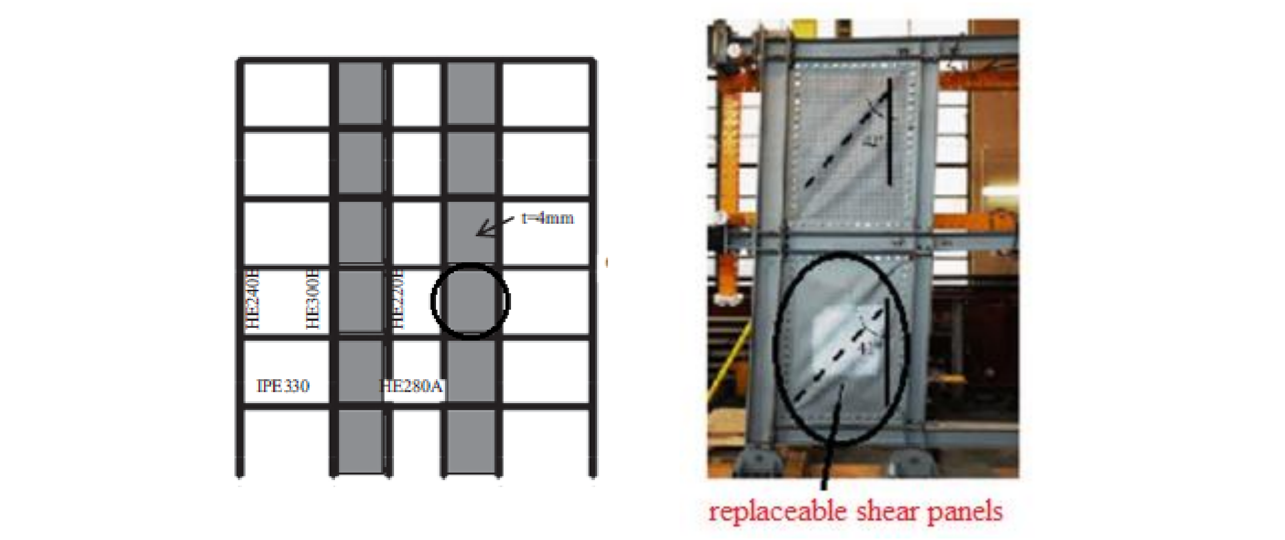

Fig. 5. SPSW replaceable thin-walled shear panel

2.6 Modified braces for CBF

This system refers to brace elements of concentric braced frames with reduced cross sections. The reduction in cross section is effected by cutting part of the web and/or part of the flanges and is introduced either near the brace ends (Fig. 6a) or at mid-span of the braces (Fig. 6b). The cross section reduction enables the designer to fine-tune the system according to current requirements of EN 1998-1, part 6. Using the RBS, the tension bearing capacity of the diagonal may be reduced with smaller influence on the member slenderness. In that way, satisfaction of the controversial code requirements for restricting brace slenderness can be achieved, providing homogeneous plasticization of all braces within the storeys. The modified braces were developed and experimentally/ analytically studied by UACEG Sofia during a national Bulgarian research project [17, 18].

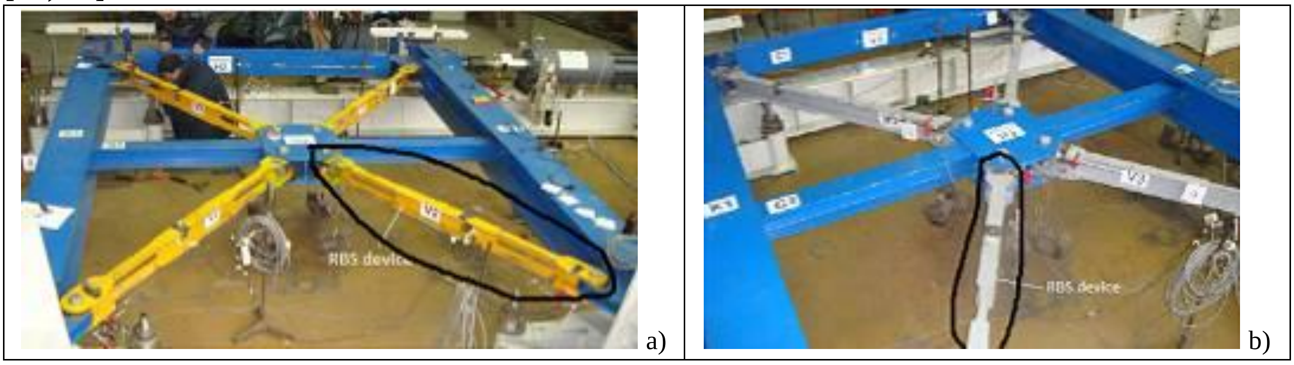

Fig. 6. Modified braces with section reductions at (a) brace ends or (b) the middle of braces

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2.7 Steel self-centring device (SSCD)

This system consists of an original steel self-centring device (SSCD) for improving the level of seismic protection of new and existing structures. This hysteretic device exhibits two technical features essential to protecting structures against the effects of an earthquake: self-centring and recovery of the structure's original dissipative capability after a seismic event. The whole system was studied within the STEELRETRO project [19]. In order to optimize the hysteretic behaviour, various grades of steel were tested, used not only in traditional structural engineering applications, but also in automotive engineering and packaging, and a full-scale prototype SSCD was finally realized. Its mechanical and dissipative performance was experimentally verified through cyclic tests, testing several configurations of the prestressing cables and dissipative elements. In Fig. 7a the assembling scheme of the dissipative device is reported, while in Fig. 7b the experimental cyclic hysteretic curve is shown.

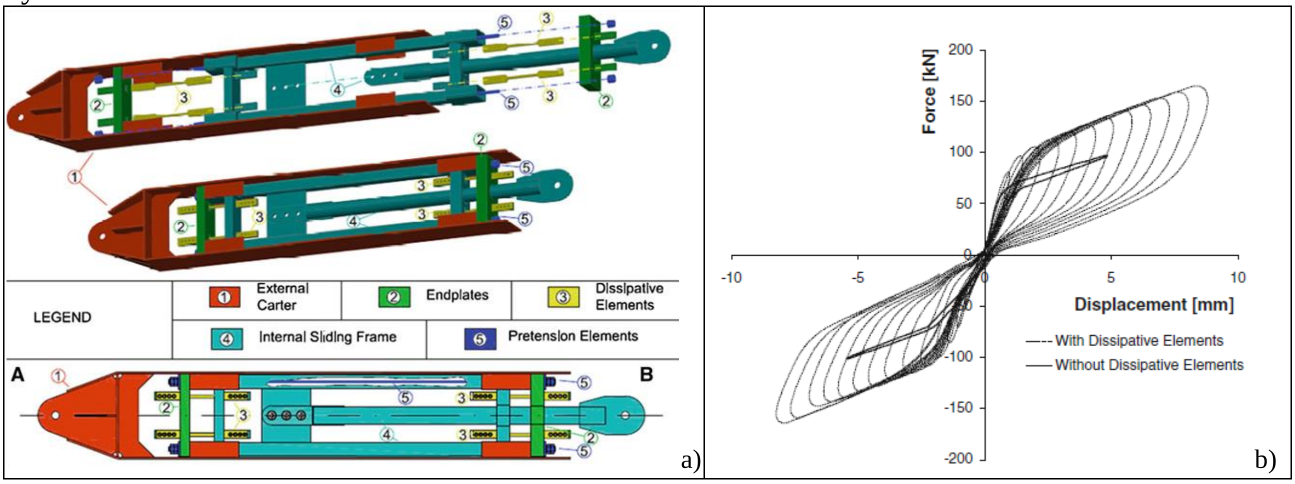

Fig. 7. SSCD: (a) assembling scheme; (b) experimental hysteretic curve

2.8 Triangle steel hysteretic device (TRSH)

The TRSH device, shown in Fig. 8a, is an easy to dimension and manufacture steel element that is subjected to bending. TRSH devices are combined with flat surface sliders or elastomeric bearing to provide base isolation with defined hysteretic energy dissipation. Tests showed a very robust behaviour and satisfying post-elastic stiffness (Fig. 8b), which is the indication of re-centring behaviour. The system was improved by means of testing and numerical calculations within the 5th FP LESSLOSS-project.

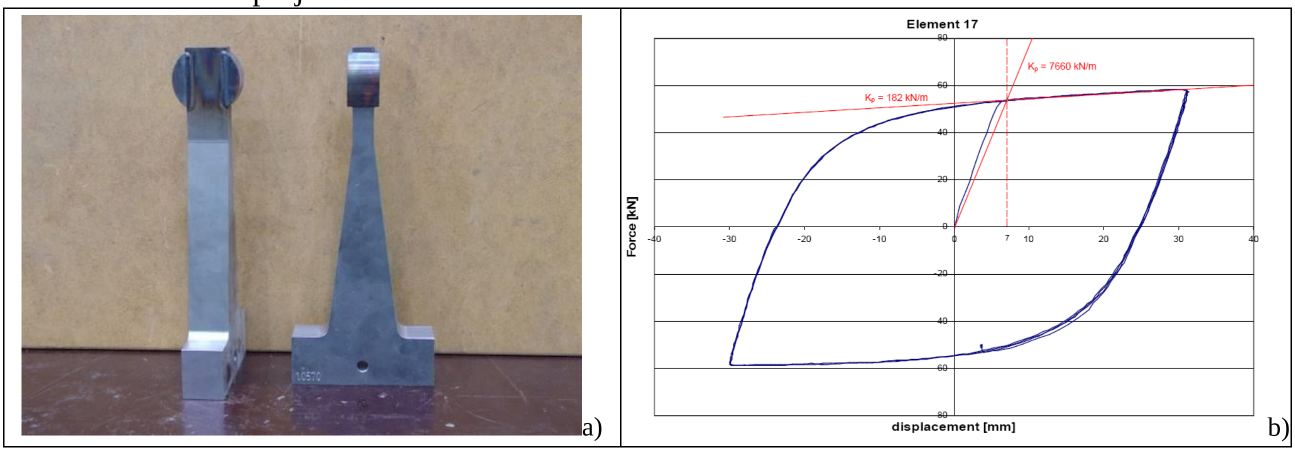

Fig. 8. TRSH: (a) devices; (b) experimental hysteretic curve

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2.9 Moon-shaped steel hysteretic device (MSSH)

The MSSH device, shown in Fig. 9, is combined with a flat surface slider or elastomeric bearing to provide base isolation with well-defined hysteretic energy dissipation. Tests show a stable and very high post-elastic stiffness with a significant inelastic plateau, indicative of good seismic behaviour. The devices are easy to replace and manufacture, offering a cost-effective solution.

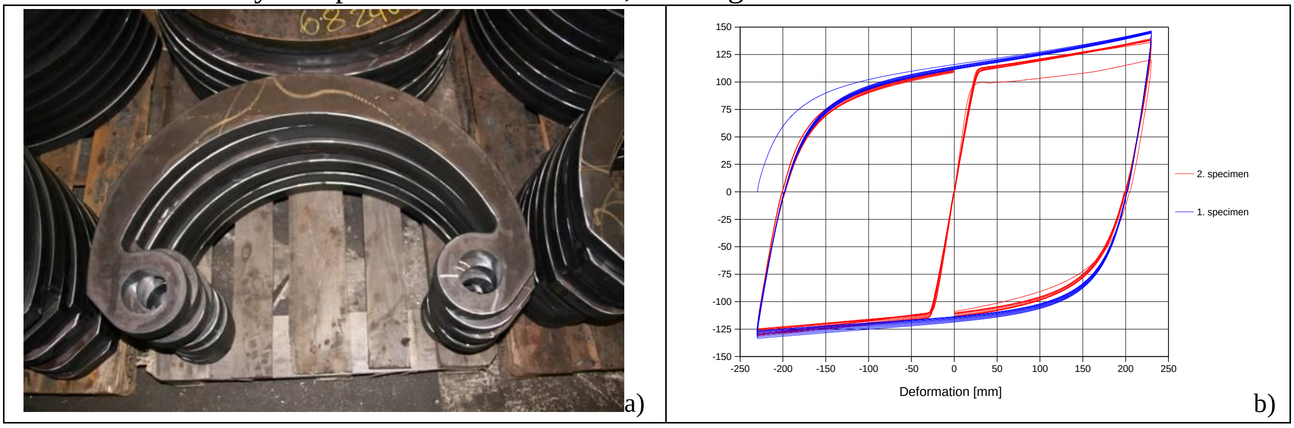

Fig. 9. MSSH: (a) devices; (b) experimental hysteretic curve

3 RELIABILITY-BASED Q-FACTOR QUANTIFICATION METHODOLOGY

The q-factor is a convention adopted by the earthquake engineering community to allow the elastic design of essentially inelastic structures. Its use is based on the idea that yielding and subsequent plastification reduce the strength demand on the structure at the expense of requiring increased ductility capacity and thus imposing damage. Rather than determining the ductility capacity of a given structural system, engineers are accustomed to using an “equivalent” behaviour q-factor. This factor is a single value, larger than 1.0, that is independent of period or height and is used to determine the required yield strength of the system by directly dividing the strength required for the system to remain elastic. EN 1998-1 provides values of the q-factor only for a very limited number of systems without any guidance on quantifying it for others. In fact, such q-values may have been proposed by researchers for each innovative system, yet without much consensus: Each proposal comes with its own definition of safety target and seismic performance assessment method, lending little confidence to the ensemble results. Unlike in the US, where the FEMA P-695 standard [20] has settled this debate, Europe has not formulated a standard methodology (barring an ECCS recommendation based on nonlinear static methods) to define and validate the q-factors. As a direct solution, a state-of-art procedure is proposed for obtaining consistent values for q based on (a) defining a class of archetype buildings (b) employing nonlinear dynamic analysis with appropriate ground motions and intensity measures (c) fully incorporating the effect of aleatory and epistemic uncertainty on systems’ performance (d) offering uniform safety across the entire population of buildings. The proposed methodology builds and improves upon existing literature [21-25] to offer a concise approach for q-factor quantification on a probabilistic basis. Firstly, models of each structural system (for example from past research) are analysed via nonlinear (static) pushover analysis to determine preliminary values for q. Then, a set of 3-7 (or more) index buildings is selected to best capture the characteristics of the envisioned population of structures where each system is applicable. Pre-normative q-factor assessment requires capturing only the salient characteristics of the intended structure types with only 2-5 buildings, spanning the parameter space in terms of, e.g., number of stories and ductility class. Normative-level assessment requires more careful discretization of the building population by considering, for example foundation flexibility, accidental eccentricities, vertical irregularities etc. Accurate nonlinear models are formed and both simulated and non-simulated (non-modelled) modes of failure are determined. Incremental Dynamic Analysis [26] is then employed, using an appropriate set of records for EU sites, together with a novel intensity measure that is designed to retain sufficiency across an entire class. The target is to comply with a maximum allowable annual probability of exceeding the collapse limit-state, adjusting the q-factor and the subsequent structural designs, until convergence is achieved. Local spectral shape and hazard curve shape effects are incorporated to increase accuracy.

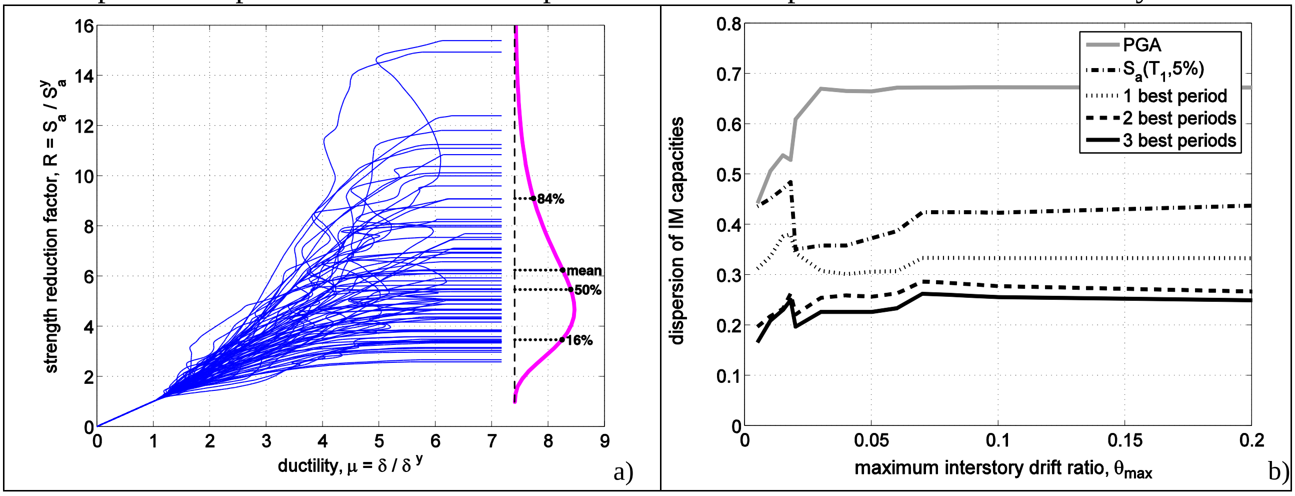

Fig. 10. a) Incremental Dynamic Analysis curves showing global collapse by flattening, together with the distribution of the achieved q-factor, in terms of the collapse fragility (purple line); b) An efficient IM can significantly reduce the dispersion of the fragility function

4 WORK PROGRAMME

The work of the INNOSEIS project is divided in 6 work packages, including its management.

WP 1 collects and critically reviews all material available for the systems under consideration. This includes the direct outcomes and reports of the research projects, additional studies performed later, application examples in real buildings etc. On this basis, information brochures were produced separately for each innovative system and then put together to form a single volume. The brochures target architects, structural engineers, public administration, software developers, construction companies and students.

WP 2 produces a document that defines a methodology for reliably quantifying values of the behaviour factors q for use in seismic design. The scope of this methodology is to achieve uniform safety against collapse for earthquakes for the different structural systems using an EN1998-compliant format.

WP 3 clarifies which systems must be qualified in accordance with EN 15129 for anti-seismic devices. For the devices within the scope of the Standard, the documentation required by EN 15129 will be created, if non-existent. For systems that fall outside EN 15129, pre-normative design recommendations will be produced that may be incorporated in the next revision of EN 1998-1. This will allow the anticipated systems to reach code-approved status.

WP 4 deals with detailed case studies of buildings in which the innovative systems are employed. The case studies refer to the design of new steel and composite buildings, as well as the seismic rehabilitation of existing buildings. Multi-storey residential or office buildings of different heights (number of stories) are selected.

WP 5 is devoted to seminars, workshops and other dissemination actions. The workshops and seminars are organized in the countries of the partner institutions. Seminars are also organized in Mediterranean countries of high seismicity. The produced material is to be distributed for free to the attending persons in printed and electronic format. In addition, a web site will be created for free access to all material.

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