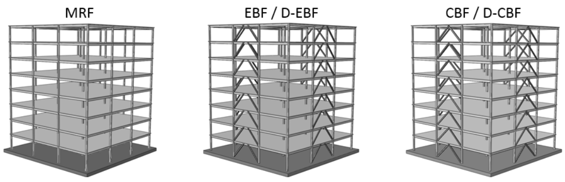
Succesful Project

HSS-SERF – HIGH STRENGTH STEEL IN SEISMIC RESISTANT BUILDING FRAMES

Goal of the project

The aim of the project was to investigate and evaluate the seismic performance of dual-steel building frames, realized from two different steel grades: Mild Carbon Steel (MCS) and High Strength Steel (HSS). Specific objectives of the research project were represented by the following: (i) to find reliable structural typologies and connection detailing for dual-steel building frames, and to validate them by tests and advanced numerical simulations; (ii) to develop design criteria and performance based design methodology for dual-steel structures; and (iii) to evaluate the technical and economical benefit of dual-steel approach involving high strength steel.



Short description of the project

Multi-storey frame structures of high strength steel members represent an innovation in seismic design in Europe. This type of structures in which mild carbon steel is used in dissipative members while high strength steel is used in non-dissipative "elastic" members, can be reliable and cost efficient.

A robust seismic resistant structure should be provided with balanced stiffness, strength and ductility among component members and connections. According to the dissipative design philosophy, such a structure will be able to dissipate a part of the energy induced by the ground motion, through plastic deformations in the dissipative zones of ductile members, e.g. beams in Moment Resisting Frames (MRF), links in Eccentrically Braced Frames (EBF), and braces in Concentrically Braced Frames (CBF). In order to avoid the premature collapse of the structure, development of plastic hinges in columns has to be prevented. To ensure such a scenario, in case of MRF's, for instance, the strong column–weak beam (SC-WB) concept applies, which in fact means to provide enough overstrength of the column with respect to adjoining beams.

In order to get an economic design of a structure, dissipative elements have to approach their plastic capacity under design forces, in order to reduce the demand on non-dissipative members (overstrength should be limited). The best way to accomplish this is not to reduce the cross-section of dissipative members and to increase the size of non-dissipative ones, but to use instead Mild Carbon Steel and High Strength Steel. To compensate for the loss of stiffness – important in MRF's of HSS columns, inherent due to reduction in steel cross-section, and to increase their axial compression strength – important in case of CBF and EBF typologies, and also to enhance fire resistance, the columns can be realized in composite solution.

Based on this conceptual framework, the purpose of "HSS-SERF" project was to investigate the seismic performance of dual-steel building frames, in order to evaluate the effectiveness of such solutions, compared with current homogeneous steel concept. MCS was aimed to be used in dissipative members, e.g. those in charge to develop plastic deformations under design earthquake action, and HSS was aimed to be used in non-dissipative members, designed to remain predominantly elastic during earthquake.

Dual-steel structures enable to fulfil by design the three critical tasks of a robust structure: (i) to secure plastic deformation capacity in structural members, targeted as dissipative, which are key members in any seismic-resistant structure; (ii) to prepare multiple routes for transfer of forces and ensure their redistribution through yielding of other members; (iii) to provide sufficient overstrength to structural members that cannot be allowed to collapse at any cost. In dual-steel structures, the role of lower-yield steel is to work like a fuse, dissipating the seismic energy through plastic deformations, while the rest of the structure remains elastic or undamaged. To achieve these global performance targets, a proper detailing is compulsory, mainly for beam to column joints, in which by conception and sizing, a good balance between dissipative and non-dissipative components is needed.

Project implemented by

The Research Center for Mechanics of Materials and Structural Safety – CEMSIG, Politehnica University of Timişoara.

Research Team

• UPT - Politehnica University of Timişoara, Romania (project coordinator)
• RIVA - RIVA Acciaio S.p.A, Italy
• VTT - Technical Research Centre of Finland
• ULG - University of Liege, Belgium
• USTUTT - University of Stuttgart, Germany
• UNINA - University of Naples "Federico II", Italy
• UL - University of Ljubljana, Slovenia
• GIPAC - Gabinete de Informática e Projecto Assistido por Computador Lda., Portugal
• RUUKKI - Ruukki Construction Oy, Finland
• UPI - University of Pisa, Italy

Main activities

The research activities of the project were divided into several working packages. The flowchart of the research is illustrated in the figure below

According to the flowchart of research, the main activities can be summarized as follows:

• Design and evaluation of the seismic performance of dual-steel multi-storey frames;

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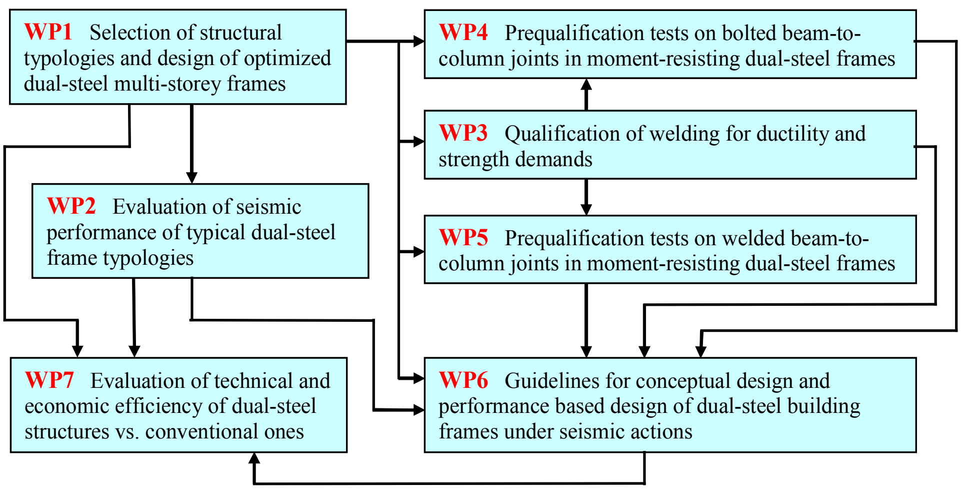
• Design and evaluation of the seismic performance of dual-steel multi-storey frames;

• Investigation of weld details and T-stubs (in correlation to welded and bolted joint assemblies);
• Investigation of bolted beam-to-column joints with columns realized as partially encased wide flange sections (PE-WF), and respectively concrete filled tubes (CFT);
• Investigation of welded beam-to-column joints with columns realized as fully encased wide flange sections (FE-WF), and respectively concrete filled tubes (CFT);
• Investigation of load introduction for CFT columns through the use of long bolts / shot fired nails;
• Elaboration of guidelines for conceptual design and performance based design (PBD) of dual-steel building frames under seismic actions;
• Evaluation of technical and economic efficiency of dual-steel structures;

In relation to the general flow chart of research, the following table summarises all working packages and nominates for each Working Package, the WP Leader and the Partners involved in the realisation of the specific tasks.

Implementation period

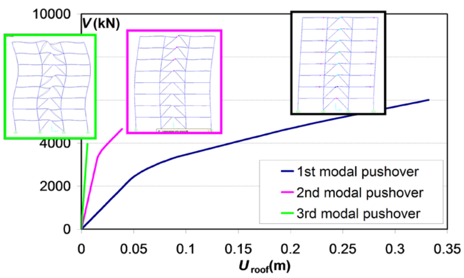
01.07.2009 – 30.06.2013.

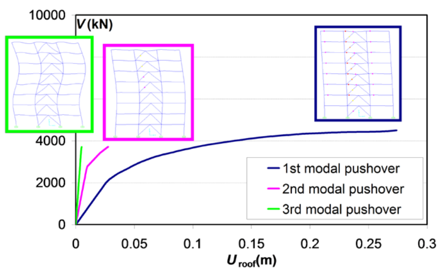


WP	WP Leader	Partners involved
WP1	GIPAC	UPT, VTT, ULG, UNINA, UL
WP2	UNINA	UPT, VTT, GIPAC
WP3	USTUTT	RIVA, ULG, UL, RUUKKI
WP4	ULG	RIVA, USTUTT, RUUKKI
WP5	UL	UPT, RIVA, USTUTT, RUUKKI
WP6	VTT	UPT, ULG, USTUTT, UNINA, UL, GIPAC, UPI
WP7	RIVA	UPT, VTT, UNINA, GIPAC, RUUKKI, UPI
WP8	UPT	RIVA, VTT, ULG, USTUTT, UNINA, UL, GIPAC, RUUKKI

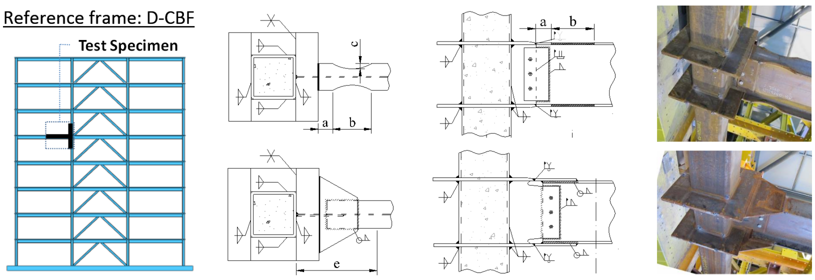
Results

A set of dual-steel multi-storey frames (moment resisting, dual concentrically braced and dual eccentrically braced) were designed according to the Eurocodes, and their seismic performance was evaluated in the first phase, using pushover analysis (see illustrations below).





The design of the multi-storey frames allowed identification of realistic member sizes for both mild carbon steel beams and high strength steel composite columns. Several practical solutions for bolted and welded beam-to-column joints were identified and designed. These are: bolted joints with hammer-heads, joints with long bolts for concrete filled tubes, welded joints with fully encased wide-flange columns and rib or cover plate stiffened beam, as well as welded joints with concrete filled tube columns and reduced beam section and cover plate stiffened beam. In addition, new T-stub configurations (with long bolts and box section) whose design is not covered by Eurocode rules, were identified and considered further in the experimental program. The joint detailing and an illustration of the reduced beam section (RBS) and cover plate (CP) joints, which were investigated at the Politehnica University of Timisoara, are shown in the figure below.



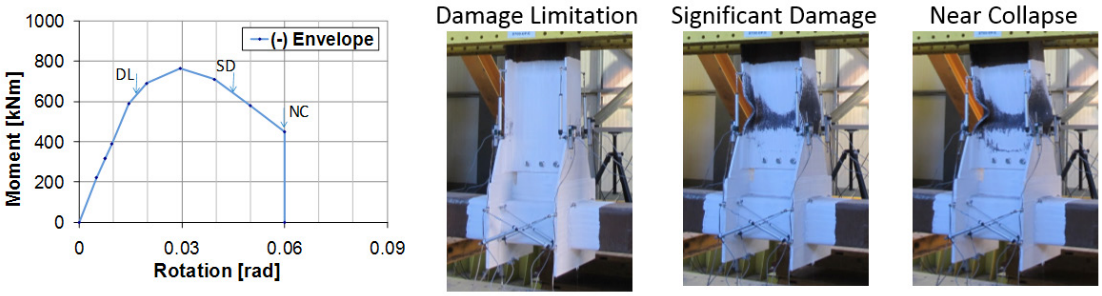
Further on, the initial set of frames was extended to include standard concentrically and eccentrically braced frames, two additional height ranges, two span ranges, and two different types of seismic action (corresponding to stiff and soft soil). Dynamic nonlinear analyses were carried out in order to assess seismic performance of this large collection of steel structures (120 cases in total).

An extensive experimental program was conducted at four Universities (i.e. University of Stuttgart, University of Liege, University of Ljubljana, and Politehnica University of Timisoara), covering investigations of material samples, weld details, bolted T-stub specimens, bolted and welded beam-to-column joints, and steel-concrete shear connection. The test set-ups are illustrated below.

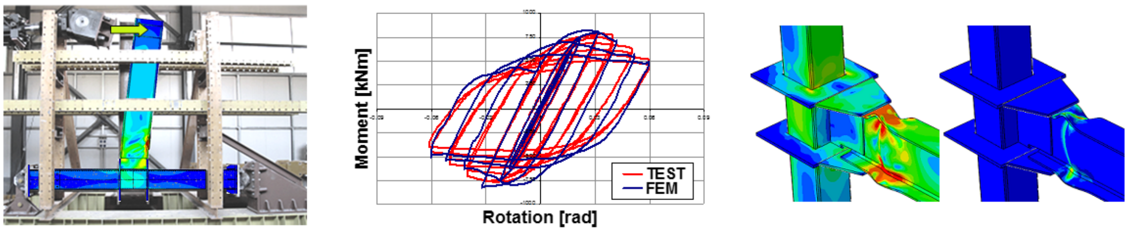



The main results obtained from the seismic performance evaluation of the dual-steel multi-storey frames, and from the experimental investigations can be summarized as follows:

- The use of HSS was proven to be an efficient solution especially in columns for CBF's (simple & dual), and in both columns and braces for EBF's (simple & dual); in contrast, the use of HSS was not an effective solution for MRF's, the seismic design procedure being governed by damage limitation;
- MRF's evidenced an adequate seismic performance with low ductility demands, and the exhibited overstrength was larger than the behaviour factor used in design;
- CBF's: the dual-system structures presented higher overstrength and behaviour factors compared to the simple solutions; however, in all cases the behaviour factors were smaller compared to the values from EN 1998-1, mainly due to the large brace ductility demand in compression; although, EN 1998-1 makes no difference between the soil condition regarding to overstrength and behaviour factors, the frames designed on soft soil presented smaller overstrength and behaviour factors;
- EBF's: the static and dynamic analyses showed that the performance of the structures designed according to EN 1998-1 was affected by the brace buckling; consequently, the behaviour factors were significantly lower compared to the values recommended by EN 1998-1; the same set of structures designed with modified capacity design criterion showed an effective performance avoiding the brace buckling, thus experiencing behaviour factors consistent to the codified values;
- The experimental investigations performed on weld details validated the adopted welding procedure, as the failure occurred in the base metal in all cases; in addition, the tests on T-stubs confirmed that the end-plate can be designed (choice of thickness and steel grade), in order to achieve sufficient ductility as requested by code provisions;
- The tests on bolted beam-to-column joints confirmed the appropriate behaviour of the proposed solutions; in addition, new analytical design rules for specific joint components that are not accounted in EN 1993-1-8, were developed and validated;
- The tests on welded beam-to-column joints evidenced a good conception and design, justified by the quasi-elastic response of the connection zone and the formation of the plastic hinge in the beam; the axial force in the columns did not influence significantly the performance of the joints;
- The load introduction tests proved that the connectors (shot fired nails) have a significant contribution to the load transfer from steel tube to concrete core, in monotonic and cyclic loading;
- An evaluation of the seismic performance of the joints was performed, and corresponding to the Significant Damage performance level, all joint configurations evidenced rotation capacities larger than 40 mrad, and therefore the seismic performance of the joints was considered acceptable;
- The state of the joints corresponding to the three performance levels (see illustrations below) was observed to reflect in a realistic manner the definition of the performance level: Damage Limitation (DL - light damage, with the component retaining the initial strength and stiffness), Significant Damage (SD - significant damage, with some margin against total collapse of the component), Near Collapse (NC - heavy damage, with low residual strength and stiffness of the component).



In addition to the experimental program, extensive numerical investigations were carried out for the beam-to-column joints. The first phase consisted in the calibration of the numerical models of the joint configurations based on the monotonic and cyclic test results. From the calibration, a set of numerical models were obtained which were capable to reproduce with a good accuracy the response of the joints in both moment-rotation curve and failure mechanism (see figures below). The second phase consisted in the extension of the experimental program with the aim to assess the influence of different parameters on the joint behaviour, e.g. influence of the concrete core, influence of the axial force in the column, and the behaviour of joints connecting two and respectively four beams. The numerical simulation program helped to achieve a better understanding of the joint behaviour, and allowed the development and validation of simple design procedures for the studied joint configurations.



The outcomes of the activities related to – design of dual-steel frames and evaluation of the seismic performance, design and detailing of beam-to-column joints, experimental investigation of weld details, T-stubs, bolted and welded beam-to-column joints – represented the main part of the Guidelines for conceptual design and performance based design of dual-steel building frames under seismic actions. Consequently, the main topics were related to: design and detailing rules for connections and joints, design methodology and criteria for MRF's, CBF's and EBF's. Conceptual design guidelines had the objective to provide the designer with information on structural configurations for which the dual-steel concept and composite action are an efficient alternative to conventional solutions. The objective of the performance based design was to provide more in-detail guidance for the design of seismic resistant structures using the dual-steel concept and composite action. Last but not least, the design and detailing rules for connections and joints aimed to provide a ductile local and overall response. The final activities were related to the evaluation of technical and economic efficiency of dual-steel structures vs. conventional ones, realized from a single grade of mild carbon steel, in order to establish conditions in which dual-steel structures are to be employed in practice. The main tasks covered the evaluation of the technical and economic efficiency of MRF's, CBF's, and EBF's.

Applicability and transferability of the results

The results are directly transferable to the steel industry and to the world of structural design of steel constructions, aiming to develop and harmonize production and design regulations. The expected advantages of HSS Dual-Steel structural solutions will allow promoting steel and steel-concrete composite constructions with respect to reinforced concrete solutions, actually more widespread in seismic countries, in Europe and outside of Europe. In recent years, significant developments in steel processing allowed obtaining high strength steels (HSS). Nowadays, in Japan and USA, HSS's are widely used for bridge and building construction. On the contrary, in Europe there are still a limited number of applications on buildings, and especially in seismic regions, although some examples exist for the use of HSS in bridge structures. The use of high strength steel within seismic resistant structures could be done considering two approaches: (i) dual-steel structures in which MCS is used for dissipative members and HSS is used in non-dissipative members; (ii) structures realized of HSS, i.e. S460 which is characterized by a certain amount of ductility and therefore could be used in structures of medium ductility class (DCM).

The research activities conducted within "HSS-SERF" project showed that the use of high strength steel in non-dissipative members (i.e. columns of CBF's & D-CBF's, respectively columns and braces of EBF's & D-EBF's) was proven to be an efficient solution. Three types of composite columns were considered in the study, i.e. PE-WF, FE-WF and CFT. Bolted and welded connection solutions were developed with the aim to achieve full strength beam-to-column joints for MRF's and moment resisting bays of the dual braced frames. Generally, it can be stated that all the proposed connection solutions have an innovative character, and their structural performance was confirmed by experimental investigations. A particular advantage of the composite columns is related to their improved resistance to fire, and for this reason, these are preferred over the bare steel columns. For example, in Japan and other Asian countries, tubular steel sections are frequently used in multi-storey frame structures, and therefore the investigated structural typologies and joint solutions have large application perspectives also in Europe.

The research project "DUAREM" – Full-scale experimental validation of dual eccentrically braced frame with removable links, represents an eloquent application of the "HSS-SERF" project. "DUAREM" project involves a full scale pseudo-dynamic test of a dual structure (Eccentrically Braced Frame combined with Moment Resisting Frames) realized using the dual-steel concept.

The proposed research aims at reducing the repair costs and downtime of a structure hit by an earthquake, and consequently more rational design approach in the context of sustainability. These objectives are to be attained through removable dissipative members and re-centering capability of the structure. The bolted links are intended to provide the energy dissipation capacity and to be easily replaceable, while the more flexible moment resisting frames would provide the necessary re-centering capability to the structure. The moment resisting frames and the columns of the eccentrically braced frames were fabricated from high strength steel, in order to keep these members in the elastic range even under strong seismic input. The full-scale pseudo-dynamic tests will be performed at the ELSA facility of the Joint Research Centre in Ispra (Italy), and will enable a realistic evaluation and validation of the structural concept and dual-steel solution.

Fields of interest

Seismic resistant structures for multi-storey building frames

Research centre

Research Centre for Mechanics of Materials and Structural Safety – CEMSIG

Financed through/by

Research Fund for Coal and Steel

- Total budget of "HSS-SERF" project: 1.763.026 €
- Budget of the Politehnica University of Timisoara: 169.560 €

Dissemination of results:

- High Strength Steel in Seismic Resistant Building Frames (HSS-SERF). D. Dubina et al., Final Technical Report, RFCS, Steel RTD, RFSR-CT-2009-00024, 2014.
- D. Dubina, A. Stratan, C. Vulcu, A. Ciutina, (2014), High Strength Steel in Seismic Resistant Building Frames, EUROSTEEL 2014, September 10-12, 2014, Naples, Italy.
- Proceedings of the International Workshop: "Application of High Strength Steels in Seismic Resistant Structures", 28-29 June 2013, Naples, Italy. Editors: D. Dubina, R. Landolfo, A. Stratan, C. Vulcu, Editura "Orizonturi Universitare", ISBN: 978-973-638-552-0, (2014).
- C. Vulcu, (2013), Seismic Performance of Dual-Steel Frames of CF-RHS and Welded Beam-to-Column Joints – Ph.D. Thesis, Editura Politehnica, Timisoara, Romania, ISBN: 978-606-554-631-8.
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