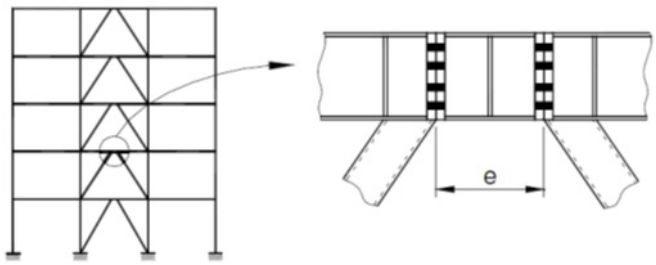
FULL-SCALE EXPERIMENTAL VALIDATION OF DUAL ECCENTRICALLY BRACED FRAME WITH REMOVABLE LINKS (DUAREM)

Goal of the project

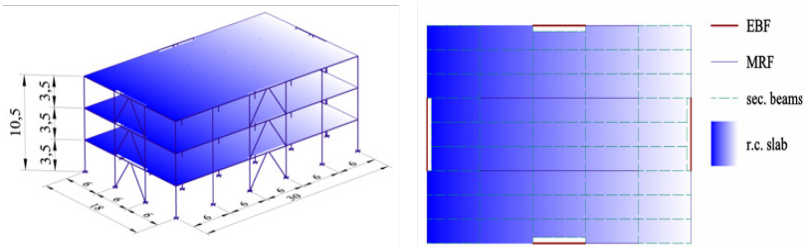
The aim of the project was to reduce the repair costs and downtime of a structure hit by an earthquake. There are three main objectives: (a) validate experimentally the re-centring capability of dual structures with removable dissipative members; (b) assess overall seismic performance of dual eccentrically braced frames; (c) obtain information on the interaction between the steel frame and the reinforced concrete slab in the link region and (d) validate the link removal technology.

Short description of the project

Improved seismic performance of multi-storey structures is to be attained through removable dissipative members ("fuse components") and re-centring capability. The concepts of removable dissipative members and re-centring capability are to be implemented in a dual structure, obtained by combining steel eccentrically braced frames with removable bolted links with moment resisting frames.



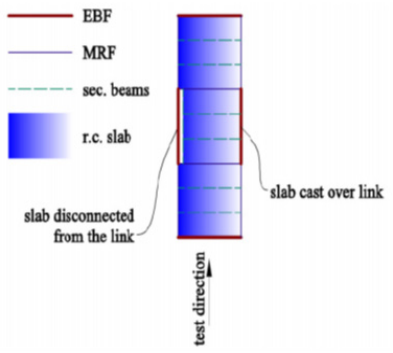
The bolted links are intended to provide the energy dissipation capacity and to be easily replaceable, while the more flexible moment resisting frames would provide the necessary re-centring capability to the structure. The columns are to be realised from high strength steel, in order to keep these members in the elastic range even under strong seismic input. The validation of the proposed solution is to be realised through a pseudo-dynamic test of a full-scale model of a dual eccentrically braced structure at the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre (JRC) in Ispra, Italy. The research will demonstrate the feasibility of the proposed concept clearing the route toward implementation into design.



The main lateral load resisting system of the prototype structure is composed of eccentrically braced frames. Additionally, there are 4 moment resisting frames on transversal directions and 10 moment resisting frames on longitudinal (test) direction, to assure the restoring forces after an earthquake. Considering that in the transversal direction the lateral force resisting system is located on the perimeter frames only, and in order to reduce the cost of the experimental specimen, it was composed of the two perimeter frames only.

Steel structural components were designed in S355 grade steel, with two exceptions. Grade S460 steel was used for columns, in order to obtain a larger capacity without increasing the stiffness. This approach helps promoting the capacity design rules. Links were designed from S235 steel grade (which was replaced during fabrication with equivalent DOMEX 240 YP B) mainly due to coping with available actuator capacities.

The floor layout is conceived in a manner that allows investigation of two different solutions of interaction between the removable link and the reinforced concrete slab. One of the two eccentrically braced frames is realised so that the beam containing the removable link is totally disconnected from the reinforced concrete slab (the south frame) and in the other EBF the beam containing removable links is connected to the slab in a conventional way (the north frame).



The structure showed an excellent seismic performance. The large scale experimental programme validated the procedure used to remove and replace damaged shear links in dual eccentrically braced frame. Small permanent deformations were recorded until the ultimate limit state earthquake level, which means that the structure is to a certain degree self-centring. Nevertheless, permanent drifts were eliminated further through removal of bolted links. Very good re-centring for frame with links disconnected from the slab was observed and only moderate cracks in the slab on the other frame were noticed (until the ultimate limit state).

If permanent plastic deformations after an earthquake are small, removing of shear links can be done simply by unbolting. If larger permanent drifts occur, as could be the case under near-field records or long-period motions, flame cutting of links and temporary braces for smooth release of forces could be employed.The system combining "fuse" components with re-centring capacity may also be extended to buckling restrained braced (BRB) and steel plate shear walls (SPSW) systems.

Project implemented by

CEMSIG - The Research Centre for Mechanics of Materials and Structural Safety - Research and Technical Development unit of Politehnica University Timisoara, at the Faculty of Civil Engineering, Department of Steel Structures and Structural Mechanics.

Research Team

- UPT - Politehnica University of Timișoara, Romania (project coordinator)
- University of Liege, Belgium
- University of Naples "Federico II"– Faculty of Architecture, Italy
- University of Ljubljana, Slovenia
- University of Coimbra, Portugal

Main activities

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

- The prototype structure was designed according to EN1990, EN1991, EN1992, EN1993, EN1994 and EN1998;
- Numerical simulations on the test structure and links were done in order to investigate the possibility to replace bolted links following significant inelastic deformations and the practical feasibility of the replacement procedure;
- Practical solutions regarding order in which bolted links need to be replaced were developed;
- A solution that uses temporary braces with viscous dampers mounted on the structure during link removal was analysed and chosen in order that the link removal process to be a safe one;

• Some experimental tests on one-storey one-span frames were used in order to calibrate the numeric model of the DUAREM test structure, before applying the link removal procedure;
• The testing sequence on the mock-up in the reaction wall facility of ELSA consists in modal evaluation, snap-back and pseudo-dynamic tests.
• The two frames of the specimen were instrumented in order to obtain information on the structural behaviour during the seismic tests, performed by using the pseudo-dynamic test method. The instrumentation consists of local displacement transducers (to monitor the links deformations and the slip in the splice connection of every EBF brace and the EBF beams from the 1st storey, in the south frame), global displacement transducers (to monitor the global longitudinal and transversal displacements of the structure), inclinometers (to monitor the rotations of the beam to column and column base joint zones) and strain gages (to monitor the yielding at the middle of the EBF braces and at the end of the MRFs beams at the 1st storey).
• Pre-test nonlinear dynamic simulations were performed on the 2D model of the experimental mock-up, using seven ground motion records, selected by matching the elastic response spectrum used in design. One record was chosen to be used in the pseudo-dynamic tests in order to evaluate the structural performance of the test structure, applied with several input levels:

Limit state	Return period, years	Probability of exceedance	a_g/a_{gr}	a_g/g
Full Operation (FO)	-	-	0.062	0.020
Damage Limitation (DL / SLS)	95	10 % / 10 years	0.59	0.191
Significant Damage (SD / ULS)	475	10 % / 50 years	1.00	0.324
Near Collapse (NC)	2475	2 % / 50 years	1.72	0.557

The following pseudo-dynamic tests were proposed and performed:

- DL/SLS (Damage Limitation/Serviceability Limit State) tests set:
  - Full operation (FO1) earthquake (ag=0.02g);
  - Damage Limitation (DL/ SLS) earthquake (ag=0.191g).
- SD/ULS (Significant Damage/Ultimate Limit State) tests set:
  - Full operation (FO2) earthquake (ag=0.02g);
  - Significant Damage (SD/ULS) earthquake (ag=0.324g);
  - Pushover (PO1) test (monotonic, with a displacement of 55 mm).
- NC (Near Collapse) tests set:
  - Full operation (FO3) earthquake (ag=0.02g);
  - Near collapse (NC) earthquake (ag=0.557g);

Results

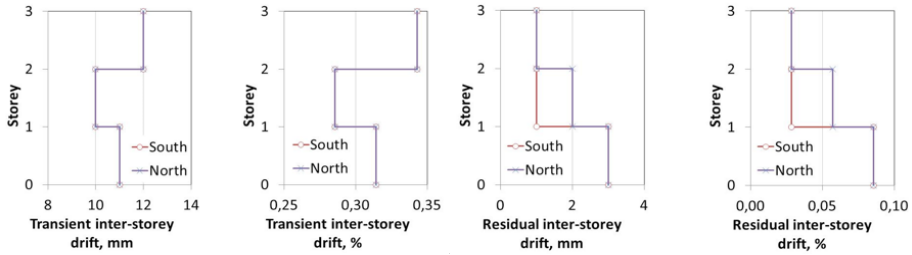
The first tests, the snap back tests, were carried out by imposing and releasing (at a very short time interval) a force at the first floor of the north frame to simulate the last seismic link removal, were according to numerical simulation is were the highest forces are locked into the device. This was achieved by pulling the structure towards the reaction wall with a piston linked by a notched bar that gave the sudden release of force when breaking after reaching its maximum. The force achieved during the snap back was lower than that given by the numerical simulation, and limited to prevent damage on the structure.

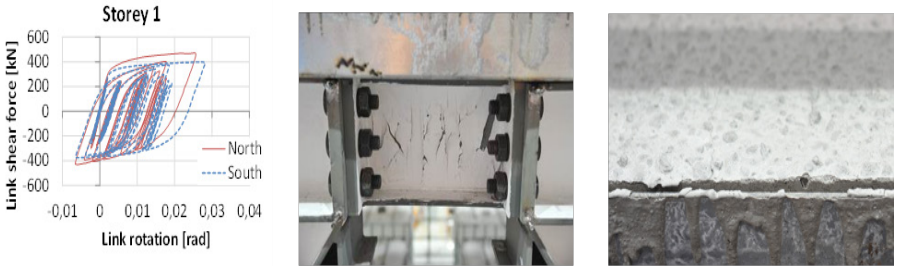
The proposed pseudo-dynamic tests, as well as two link replacement operations, were performed and information about the seismic performance of the test specimen, the link replacement feasibility and concrete slab influence were obtained.

DL/SLS tests set results:

• FO1 test was performed in order to assess the elastic response of the structure with the initial (first) set of links, the selected seismic record being scaled to have the PGA of 0.02g. During this first test, the structure manifested an elastic response, in the non-dissipative elements, as well as in the dissipative ones (including the links). This means that there were no residual top displacements or inter-storey drifts of the structure, the maximum top displacement being also small.

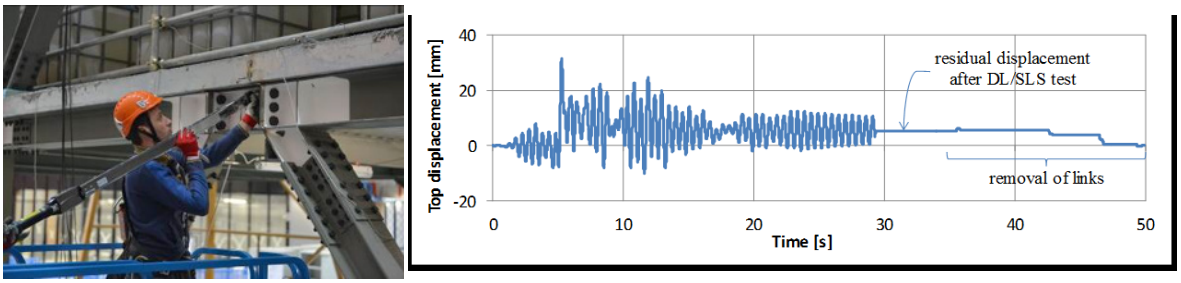
• DL/SLS test was performed afterwards, in order to simulate a moderate earthquake, causing moderate structural damage, the selected seismic record being scaled to have the PGA of 0.191g. During this test, no yielding was observed in the elements outside links. Small maximum plastic deformations occurred in links and no slips have occurred in the EBF braces and beams splice connections. Beam to column and column bases joint zones manifested small rotations. Minor cracks were observed in the concrete slab. The structure exhibited low residual top displacement. Also low residual inter-storey drifts were observed.





First link replacement (LR1):

• Because after the DL/SLS test the structure exhibited low residual top displacement and low residual drifts were observed, the decision was to remove the first set of damaged links, by removing the bolts, on a level by level basis, starting from the lower level to the upper one. The low value of the residual top displacement from the end of the DL/SLS test decreased after the elimination of the damaged links. A better re-centring was observed in the south frame, where the concrete slab is disconnected from the link. After unscrewing the bolts, a hydraulic jack had to be used for pushing apart the braces, in order to pull out the links. A new set of unused links was then mounted into the structure.

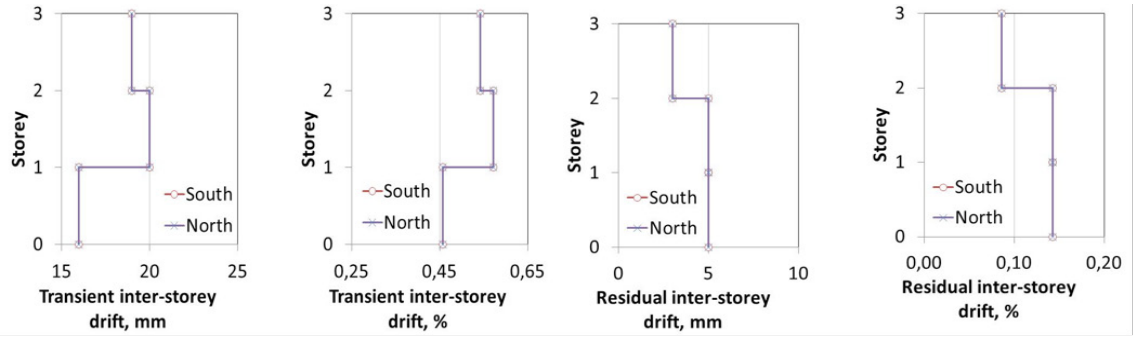


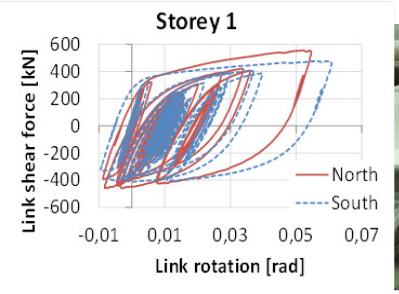
SD/ULS tests set results:

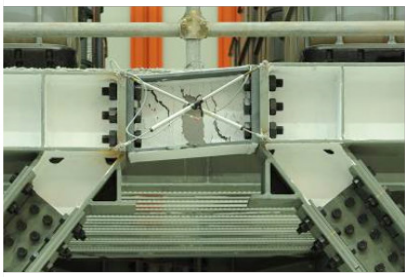
• FO2 test was performed in order to assess the elastic response of the structure with the new (second) set of links, the selected seismic record being applied with a scaling factor of 0.02. During this second FO test, the structure exhibited a similar behaviour as the FO1 test. This means that the structure manifested an elastic response, in the non-dissipative elements, as well as in the dissipative ones (including the links) and there were no residual top displacements or inter-storey drifts of the structure, the maximum top displacement being also small.

• SD/ULS test was performed in order to simulate a stronger earthquake, causing larger structural damage, the selected seismic record being scaled to have the PGA of 0.324g. During this test, no yielding was observed in the elements outside links. Moderate maximum plastic deformations occurred in links and no slips have occurred in the EBF braces and beams splice connections. Beam to column and column bases joint zones manifested slightly larger rotations. Moderate cracks were observed in the concrete slab. The structure exhibited still quite low residual top displacement.

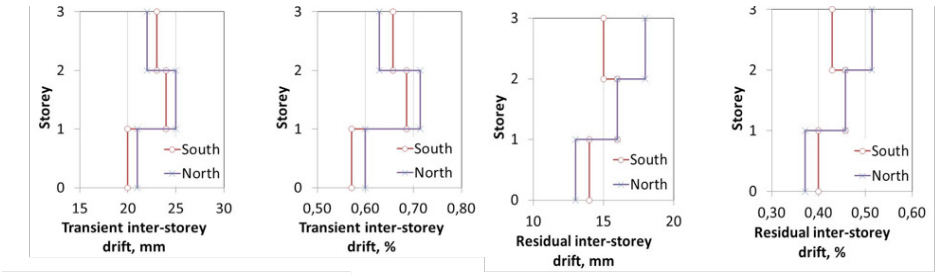
• Also low residual inter-storey drifts were observed.

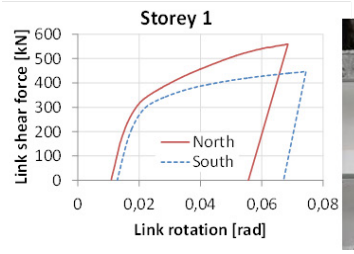


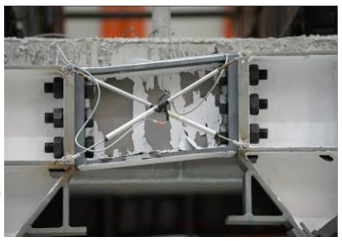




• P01 test (a monotonic pushover test until an additional displacement of 55 mm) starting from the end of the SD/SLS test position was necessary. This was done to obtain larger residual displacements that were necessary in order to validate the feasibility of the link removal process and re-centring of the structure. During this test, no yielding was observed in the elements outside links. Higher maximum plastic deformations occurred in links and no slips have occurred in the EBF braces and beams splice connections. Beam to column and column bases joint zones manifested larger rotations. More visible cracks were observed in the concrete slab. After this test, the structure exhibited significant larger residual top displacement. Larger residual inter-storey drifts amounting were observed.

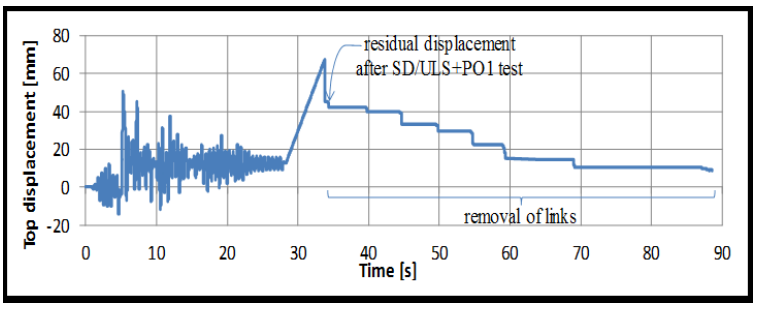






Second link replacement (LR2):

• Because after the P01 test the structure exhibited significant larger residual top displacement and larger residual drifts were observed, the decision was to remove the second set of damaged links, by flame cutting both the web and flanges of the links, from the top storey downwards. The value of the residual top displacement from the end of the P01 test was decreased after the elimination of the damaged links. Again a better re-centring was observed in the south frame, where the concrete slab is disconnected from the link. Although the hydraulic jack was not necessary to remove the links, it was needed for placing the new set of links back into the structure. A new set of unused links was then mounted into the structure.



NC tests set results:

- TF03 test was performed in order to assess the elastic response of the structure with the new (third) set of links, the selected seismic record being scaled to have the PGA of 0.02g. During this third FO test, the structure exhibited a similar behaviour as the first two FO tests. The structure manifested an elastic response, in the non-dissipative elements, as well as in the dissipative ones outside links and very small residual deformations in links and there were no residual top displacements or inter-storey drifts of the structure, the maximum top displacement being also small.
- NC test was proposed in order to simulate a much stronger earthquake and to obtain extensive damage throughout the structure, the re-centring capability being lost due to yielding in other members apart from the links, the selected seismic record being applied with a scaling factor of 0.557. This test was prematurely stopped because the available actuator capacity (1000 kN per frame at every floor) was not enough to carry it out with the imposed null torsion at every floor.
- Another cyclic pushover test (PO2) with maximum displacement amplitudes of 150 mm was further proposed, after the actuators' release of force from the NC test and afterwards a final cyclic pushover test (PO3) with maximum displacement amplitude of 400 mm.
- The last three tests brought extensive plastic behaviour throughout the entire structure. First of all, very large maximum plastic deformations occurred in links, failure occurring in the welds of the links to the end plates and also between web and flanges for the first two levels. Significant damage was also observed in the column bases zones and at the end of the MRFs beams (strains 3 times larger than the yield one), just outside the haunch. Beam to column and column bases joint zones manifested very large rotations. The concrete slab was heavily deteriorated in the north frame.






- Due to the presence of the slab over the links, the north frame is more rigid and has a larger capacity than the south frame. This makes more difficult the re-centring of the north frame with respect to the one of the south frame, but the residual drifts were still lower than the erection tolerances.
- The dual eccentrically braced structure showed an excellent performance at the SLS and ULS earthquakes. Small permanent deformations were recorded for both seismic intensity levels, which are within the erection tolerance limits defined in EN 1090. This behaviour occurs mostly due to the large post-elastic stiffness of the system, provided by the moment-resisting frames. Small permanent deformations effectively mean that the structure is self-centring to a certain degree.

Implementation period

01.06.2010 - 01.08.2014

Applicability and transferability of the results:

After the pseudo-dynamic experimental validation of the main concepts, the experimental results interpretation and numerical model validation and calibration, the system can be applied to new, higher, multi-storey steel dual structures in seismic areas. A design methodology for dual eccentrically braced steel frames with removable links thus can be developed, as well as a guide for link replacement technology. The system may also be extended to buckling restrained braced (BRB) and steel plate shear walls (SPSW) systems.

Fields of interest

• Re-centring structures; Performance-based design; Bolted link connections; Pseudo-dynamic structural experimental tests.

Financed through/by

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• European Community's Research Fund for Coal and Steel under grant agreement n° RFSR-CT-2009-00024 "High strength steel in seismic resistant building frames"

Research centre

CEMSIG - The Research Centre for Mechanics of Materials and Structural Safety,
Politehnica University of Timisoara.

Dissemination of results:

• Dubina, D., Stratan, A., Dinu, F. (2011). "Re-centring capacity of dual-steel frames", Steel Construction: Design and Research, Vol. 4, No. 2, pp. 73-84.
• Ioan, A. (2011). "Seismic response of dual steel eccentrically braced frames with removable links". Scientific Journal - Mathematical Modelling in Civil Engineering, vol.7, no.4, ISSN 2066 – 6926, pp. 101- 110 – BDI Journal.
• Stratan, A., Ioan, A., Dubina, D. (2012). "Re-centering capability of dual eccentrically braced frames with removable bolted links". Proceedings of the 7th International Conference on Behavior of Steel Structures in Seismic Areas (STESSA), 9-11 January 2012, Santiago, Chile, ISBN 978-0-415-62105-2, pp. 723-728 – ISI Web of Knowledge conference.
• Ioan, A., Stratan, A., Dubina, D., Taucer, F. (2012) – "Dual Steel Eccentrically Braced Frames with Bolted Links – Simulation of Safe Removal Process". Proceedings of the First International Conference for PhD students in Civil Engineering (CE-PhD), 4-7 November 2012, Cluj-Napoca, Romania, ISBN 978-973-757-710-8, pp. 220-227.
• Ioan, A., Stratan, A., Dubina, D. (2013). "Numerical Simulation of bolted links removal in eccentrically braced frames". Pollack Periodica, vol. 8, no.1, ISSN 1788-1994, pp. 15-26 – BDI Journal.
• Dubina, D., Stratan, A., Florea, D., Ioan, A. (2013). "Sisteme structurale cu componente disipative de siguranta seismica" (in Romanian). AICPS Review, no. 1-2 ISSN 2067-4546, pp. 41-50.
• Stratan, A., Ioan, A., Dubina, D., D'Aniello, M., La Manna Ambrosino, G., Landolfo, R., Taucer, F., Poljansek, M. (2013). "Pre-test numerical simulation and experimental program on a dual eccentrically braced frame with replaceable links". "XXIV Giornate italiane della Costruzione in Acciaio", Torino, 30 September – 2 October 2013, ISBN 978-88-905870-0-9, pp. 867-876.
• Ioan, A. (2013). "Pre-testarea numerica a unui cadru cu bare disipative demontabile supus la incercari pseudo-dinamice" (in Romanian). AICPS Review, no. 3, ISSN 2067-4546, pp. 63-71. (ZAT2013)
• Ioan, A., Stratan, A., Dubina, D. "Evaluation of restoring capacity of dual steel EBFs with removable links". Pollack Periodica (accepted for publication)
• Stratan, A., Ioan, A., Dubina, A., Taucer, F., Poljansek, M. (2013). "Pre-test numerical simulations and experimental program on dual eccentrically braced frame with removable links". International Workshop "High Strength Steel in Seismic Resistant Structures - HSS-SERF" 28-29 June 2013, Naples, Italy, ISBN 978-973-638-552-0, pp. 137-148.
• Stratan, A., Ioan, A., Dubina, D., Taucer, F., Poljanšek, M., Molina, J., Pegon, P., D'Aniello, M., Landolfo, L. 2014. „Experimental program for large-scale tests on a re-centring dual eccentrically braced frame". EUROSTEEL 2014 (7th European Conference on Steel and Composite Structures), 10-12 September 2014, Napoli, Italy.
• Ioan, A., Stratan, A., Dubina, D. 2014. „Link replacement order in high-rise re-centring dual eccentrically braced frames". EUROSTEEL 2014 (7th European Conference on Steel and Composite Structures), 10-12 September 2014, Napoli, Italy.
• Stratan, A., Ioan, A., Dubina, D., Poljanšek, M., Molina, J., Pegon, P., Taucer, F. (2014). „Dual eccentrically braced frames with removable links: Experimental validation of technical solution through large-scale pseudo-dynamic testing". 5CNIS&1CNISS (5th National Conference of Earthquake Engineering and 1st National Conference on Earthquake Engineering and Seismology), 19-20 June 2014, Bucharest, Romania.
• Stratan, A., Ioan, A., Dubina, D., Poljanšek, M., Molina, J., Taucer, F., Pegon, P., Sabau, G. (2014). "Experimental validation of re-centring capacity of eccentrically braced frames with removable links" – sent to Engineering Structures Journal - ISI Web of Knowledge journal.

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