

## **Dual-Steel Eccentrically Braced Frames with Bolted Links – Simulation of Safe Removal Process**

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### **Abstract**

*Current seismic design philosophy is based on dissipative structural response, which implicitly accepts damage to the main structure and significant economic losses. Repair of the structure is often impeded by the permanent (residual) drifts of the structure. 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-centring capability of the structure, concepts that 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 of the structure are to be realised from high strength steel, in order to keep these members in the elastic range even under strong seismic input. Practical solutions regarding order in which bolted links need to be replaced are proposed. In order that the link removal process to be a safe one, there is analyzed and chosen a solution that uses tension rods with viscous dampers mounted on the structure during link removal. Once the seismic link is removed from the structure, this system slowly releases the accumulated forces and the structure comes back to its initial position.*

### **Rezumat**

*Practica actuală de proiectare seismică se bazează pe răspunsul disipativ al structurilor, care acceptă în mod implicit deteriorări ale structurii și pierderi economice semnificative. Repararea structurii este adesea împiedicată de deplasările permanente (reziduale) ale structurii. Cercetarea propusă are ca scop reducerea costurilor reparațiilor și a timpului de nefuncționare a unei structuri supuse unui cutremur, și, prin urmare, o abordare de proiectare mai rațională, în contextul dezvoltării durabile. Aceste obiective se vor atinge cu ajutorul unor elemente disipative demontabile și a capacității de revenire a structurii, concepte care vor fi implementate într-o structură duală, obținută prin combinarea unor cadre metalice contravântuite excentric cu linkuri demontabile prinse cu șuruburi, cu cadre necontravântuite. Linkurile prinse cu șuruburi sunt destinate să furnizeze capacitatea de disipare a energiei și să fie ușor de înlocuit, în timp ce cadrele necontravântuite, mai flexibile, ar oferi capacitatea de revenire necesară structurii. Stâlpii structurii se vor realiza din oțel de înaltă rezistență, pentru ca aceste elemente să rămână în domeniul elastic chiar și în cazul unui cutremur puternic. Se propun soluții practice privind ordinea în care linkurile detașabile trebuie înlocuite. Pentru ca procesul de înlocuire a linkurilor să fie unul*

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sigur, este analizată și aleasă o soluție care utilizează sisteme de contravântuiri întinse cu disipatori, montate pe structura în timpul procedurii de înlocuire a linkurilor. După ce linkul este eliminat, acest sistem eliberează treptat forțele acumulate și structura revine la poziția inițială.

**Keywords:** re-centering capability, bolted links, eccentrically braced steel frames, dual frames.

## 1. Introduction

Current seismic design philosophy is based on dissipative structural response, which implicitly accepts damage to the main structure and significant economic losses. Repair of the structure is often impeded by the permanent (residual) drifts of the structure. 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-centring capability of the structure, concepts that are to be implemented in a dual structure, obtained by combining steel eccentrically braced frames with removable bolted links with moment resisting frames [1]. 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 of the structure 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) facility at JRC in Ispra.

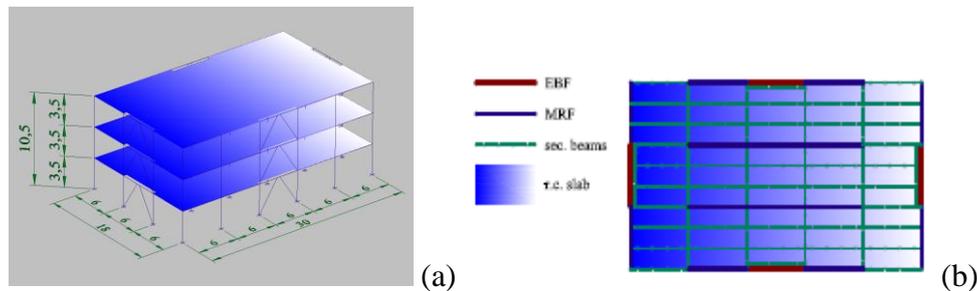


Figure 1 - General view (a) and plan layout (b) of the prototype structure

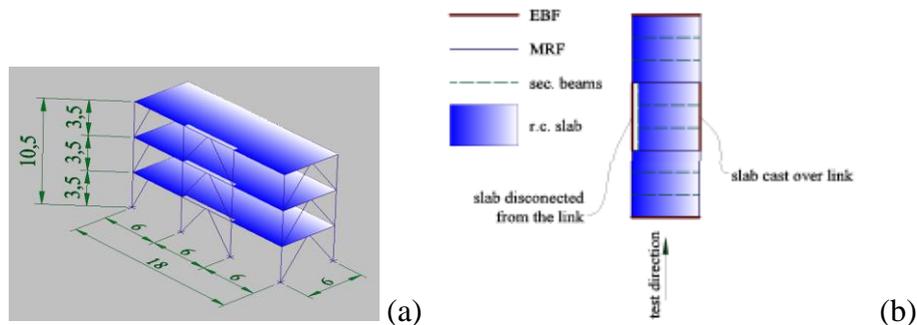


Figure 2 - General view (a) and plan layout (b) of the test structure

There was previously investigated [2] a design approach aiming to concentrate damage on removable and easy to repair structural elements ("structural fuses"), with the main structure designed to remain elastic or with minor inelastic deformations. A systematic procedure was proposed to design buildings with metallic structural fuses.

Application of the concept of removable dissipative members to eccentrically braced frames (EBFs), where links act as dissipative zones, is presented in Fig. 3 [3], [4].

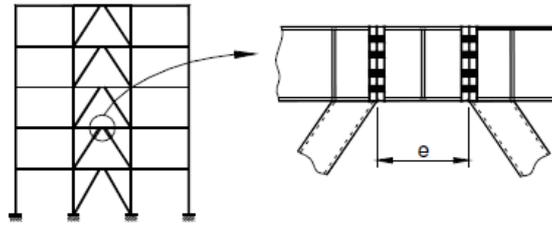


Fig. 3. General view (a) and plan layout (b) of the prototype structure

The aim of the present paper is to describe practical solutions regarding order in which bolted links need to be replaced. In order that the link removal process to be a safe one, there is analyzed and chosen a solution that uses tension rods with viscous dampers mounted on the structure during link removal. Once the seismic link is removed from the structure, this system slowly releases the accumulated forces and the structure comes back to its initial position.

Because in a dynamic nonlinear time history analysis in SAP2000 elements (the links) can't be removed, a simplified SDOF system was analyzed, representing the elimination of the links from the first story, without taking account of the torsion effects upon the structure (see Chapter 2). The dynamic response in terms of peak force is very close to the static one in the SDOF, justifying static analysis of the MDOF system (see Chapter 3).

## 2. Link removal procedure: SDOF model

The elastic structure was modeled by a vertical cantilever with a height of 3.5 m and the same stiffness of the reference structure with all shear links removed. The mass was then computed in order to obtain the same period of vibration in the SDOF model and the reference MDOF model (with shear links removed). A value of 2% Rayleigh damping was used. The vertical cantilever representing the structure has the following properties:

- Period of vibration  $T=2.68$  sec;
- Stiffness:  $K=22121$  kN/m (Height  $h= 3.5$  m; flexural stiffness  $EI=316152$  kNm<sup>2</sup>);
- Mass  $M=4024.6$  tones.

A time history analysis was performed, under a horizontal force at the top of the cantilever with the load pattern below (see Figure 4). The amplitude of the force was 535 kN, generating a displacement of 24.2 mm (the one obtained in the 3D model of the test structure from the step just before the elimination of the second link from the first story) at the time the force is suddenly dropped to zero.

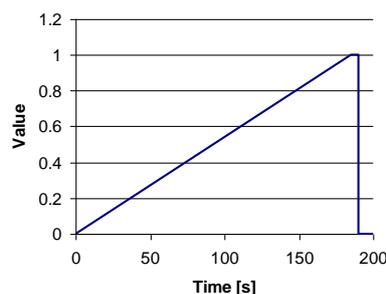


Figure 4. Time history function definition

In order to have a safe link removal procedure (avoiding vibrations of the structure), there were analyzed two solutions, described in the following chapters.

### 2.1. Solution 1: simple bracing

In this first solution, for the safety bracing system there was used a tension brace with an area of  $2.110 \times 10^{-3} \text{ m}^2$  (CHS 139.7x5 mm section), that releases force through manual or hydraulic de-tensioning.

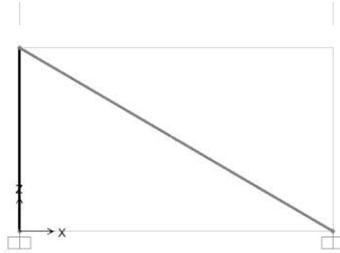


Figure 5. SDOF model with brace layout

The following top displacement and brace force in time charts were obtained:

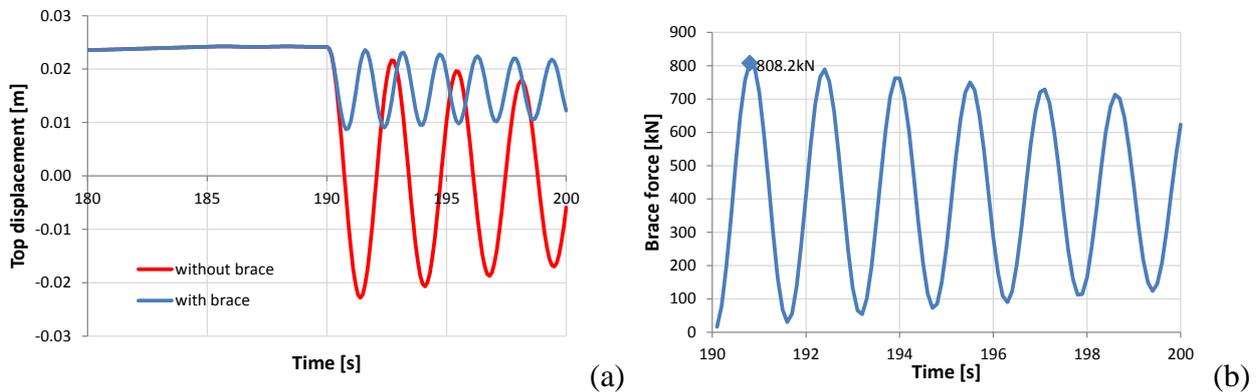


Figure 6. Top displacement (a) and brace force (b) in time charts

It can be observed that the top displacement amplitude decreases by adding the tension brace but the structure still vibrates. Moreover, there is an important amplification (about 2) of the force in the brace with respect to the static force. So, a second solution was adopted, described below.

### 2.2. Solution 2: bracing with damper

In this second solution, instead of only a tension member there was used a bracing system composed of a brace in series with a damper, that was modeled using a Nlink element (dashpot in series with a linear spring).

The dashpot properties are the following:

- $c=2e4 \text{ kN}\cdot\text{s/m}$  (damping coefficient twice the value of a single damper and close to the critical one  $c_{cr}=18871 \text{ kN}\cdot\text{s/m}$ );
- $\alpha = 1$ .

The elastic spring represents the axial stiffness of the (two – as in the 3D model) CHS 139.7x5 braces ( $EA/L=2*64095 \text{ kN/m}$ ), section chosen because the response was much closer to the classical response of a critically damped SDOF system, which should be the desired response from the perspective of safety in link removal process.

After running the same analysis described in paragraph 0, the following results were obtained:

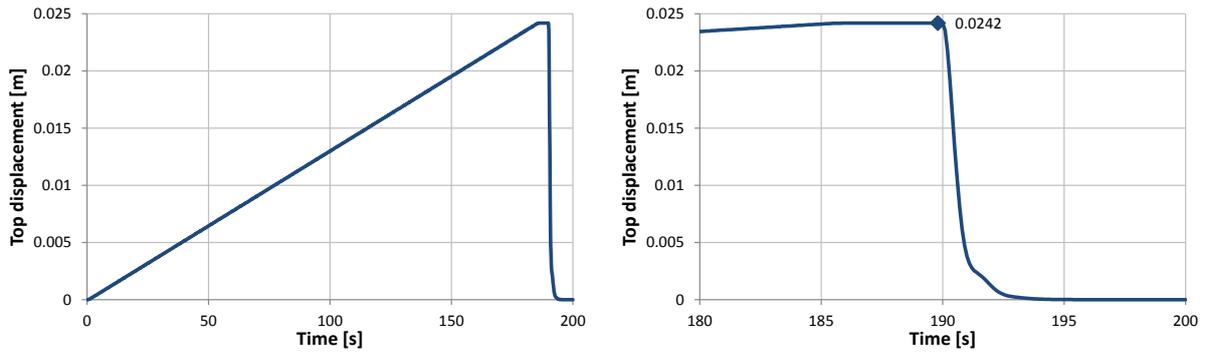


Figure 7. Top displacement in time charts

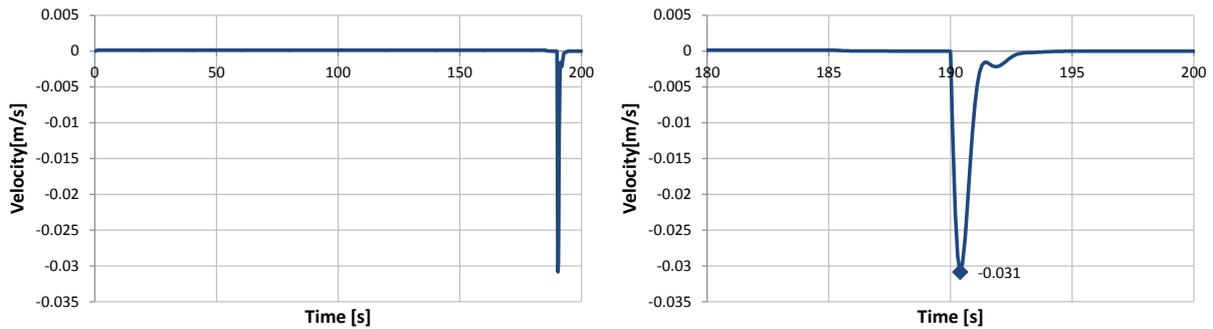


Figure 8. Velocity in time charts

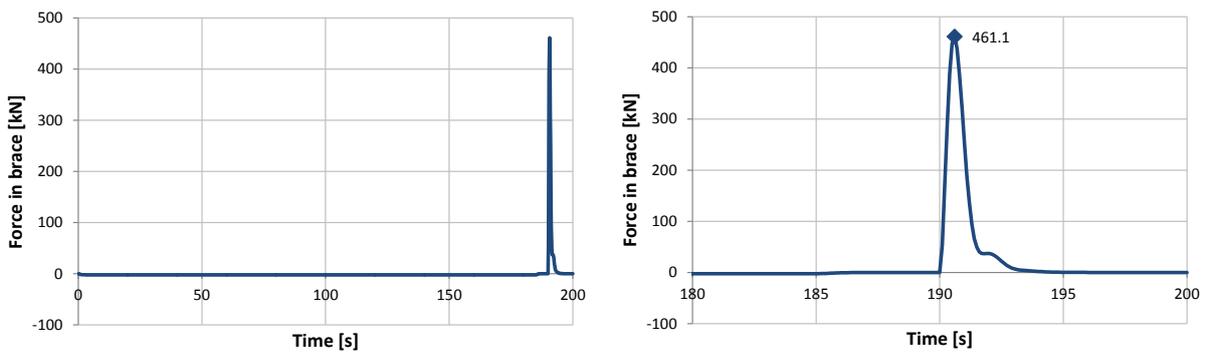


Figure 9. Brace force in time charts

It can be observed that the structure doesn't vibrate, meaning that this is the best solution from safety considerations. The maximum velocity is of 31 mm/s and the brace force in the MDOF model is of  $461.1/2 = 230.6$  kN (there are two braces per story in the test structure).

### 3. Link removal procedure: MDOF model

Because in a dynamic nonlinear analysis in SAP2000 the links of the structure can't be eliminated, for the MDOF model a static nonlinear analysis was run.

In case of the SDOF system – solution 2, the brace force obtained from the dynamic nonlinear analysis, of 230.6 kN, is with 7% smaller than the one obtained from static linear analyzing the same model, that is of 246.2 kN. Thus, the dynamic response in terms of peak force is very close to the static one. This justifies static analysis of the MDOF system.

Because of the damper presence, the two bracing systems per storey are to be unloaded simultaneously (see Figure 10).

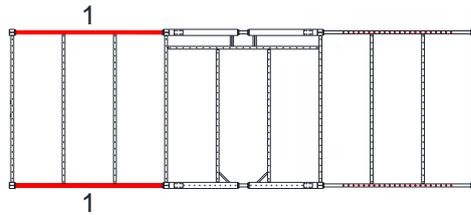


Figure 10. Bracing systems layout per storey

In order to simulate the link removal procedure following a damaging earthquake, the static nonlinear staged construction analysis from SAP2000 was used. This analysis allows sequential application and removal of loads and/or parts of the structure. Nonlinear structural behavior is possible.

There was established, on a 2D model of the test structure, that the link removal order to be from up towards down, as described in the following figures:

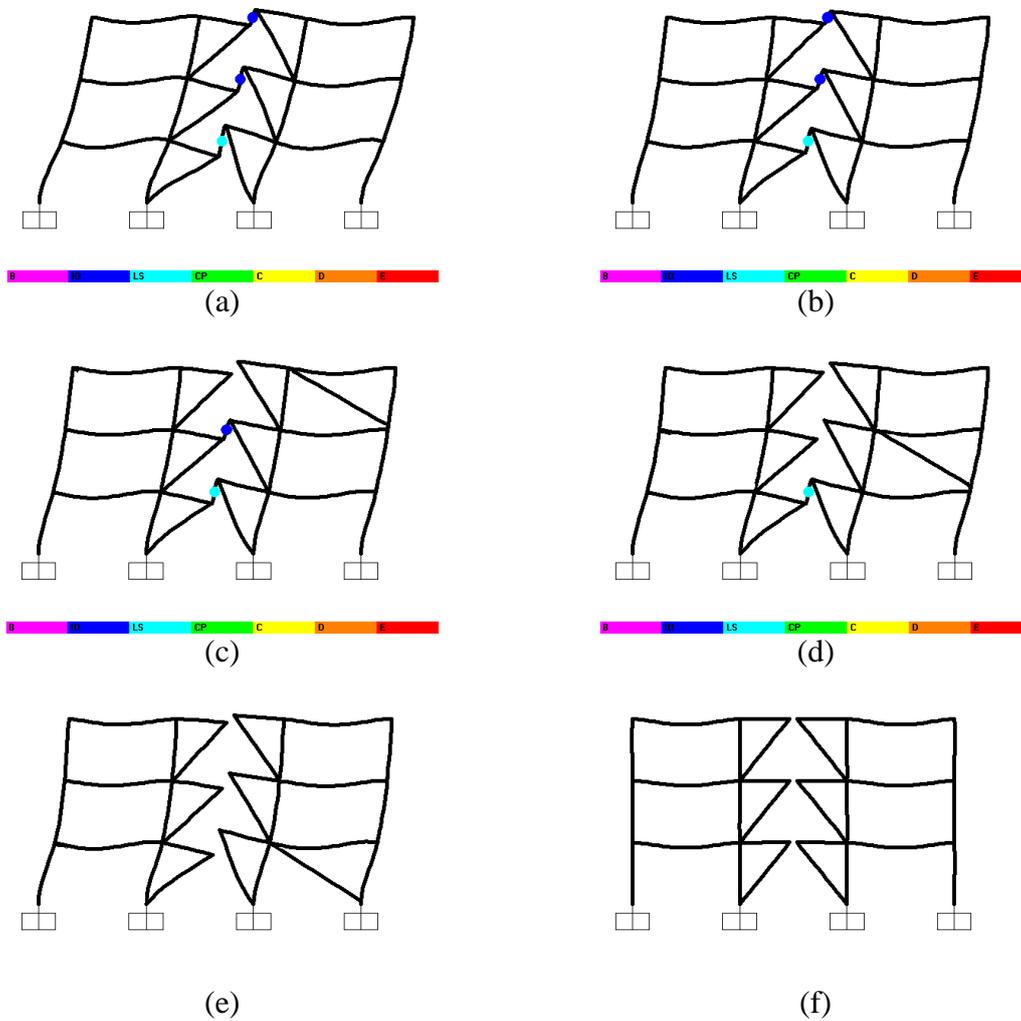


Figure 11. Height-wise link removal order

Firstly the structure is loaded with gravitational forces and afterwards with lateral forces up to a

displacement corresponding to the maximum pushover force (pseudo-dynamic simulation of seismic loading) (Figure 11.a), then it is unloaded (Figure 11.b).

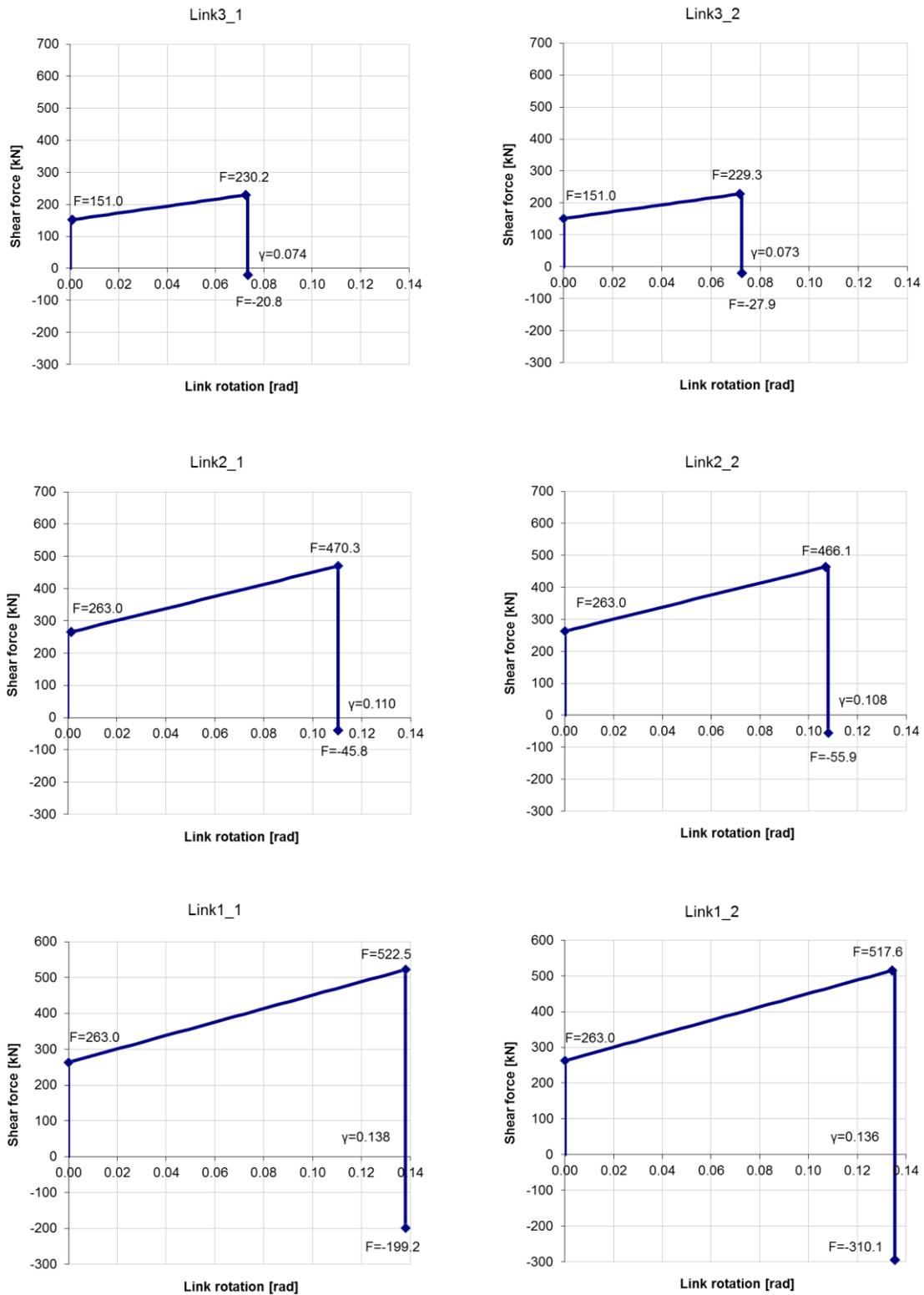


Figure 12 – Links’ force-rotation curves

After installing the bracing systems at the third level, the link is removed by flame cutting (Figure 11.c) and afterwards, the brace forces are released through the dampers and the bracing systems are

eliminated. The procedure is repeated for the second (Figure 11.d) and the first levels (Figure 11.e) and, in the end, there are removed the bracing systems from the first story (Figure 11.f) and the structure comes back to its initial position. The links elimination from one story doesn't have much influence on the links from the other stories, the procedure being almost story independent. The force-rotation charts for the links at all three stories in the two parallel frames are presented below.

#### 4. Conclusions

Bolted links are the dissipative components in the DUAREM tests structure. Residual forces and deformations are present in the links after they have experienced plastic excursions during an earthquake. Removing a damaged link involves redistribution of residual forces to other parts of the structure, more precisely from eccentrically braced frame to moment resisting ones. Numerical simulation of the link removal order showed that there is negligible redistribution of forces among stories. Therefore, the link replacement procedure can be performed on a story by story basis, starting from the least loaded to the most loaded one (from the upper story toward the lower one).

The technically easiest way to release the forces in links is by flame cutting the web and flanges of the link. However, there is concern that this solution might lead to a sudden release of link shear force and therefore might be dangerous to the operating personnel. Therefore an improvement of the solution was analyzed in the present article. It employs some bracing systems (a tension brace in series with a damper) that are installed in one moment resisting bay prior to link removal. Once the links are flame cut, the forces locked in the links are smoothly transferred to the temporary bracing system. Once all links from a story are removed, all structural components from that story are in elastic range of response. Therefore, as the brace forces are released through braces with dampers, the structure recovers its initial (plumb) position, becoming free of any locked-in forces.

#### Acknowledgement

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#### 5. References

- [1] Stratan A., Ioan A., Dubina D., "Re-centering Capability of Dual Eccentrically Braced Frames with Removable Bolted Links", Proceedings of the STESSA (Behavior of Steel Structures in Seismic Areas) Conference, 9-11 January, Santiago, Chile, pp. 723-728, 2012.
  - [2] Stratan, A. & Dubina, D. 2004. Bolted links for eccentrically braced steel frames. *Proc. of the Fifth AISC / ECCS International Workshop "Connections in Steel Structures V. Behavior, Strength & Design"*, June 3-5, 2004. Ed. F.S.K. Billiard, A.M. Greasing, G.J. van der Vertex. Delft University of Technology, The Netherlands, pp. 223-232.
  - [3] Dubina, D., Stratan, A., Dinu, F. 2008. Dual high-strength steel eccentrically braced frames with removable links. *Earthquake Engineering & Structural Dynamics*, Vol. 37, No. 15, p. 1703-1720.
  - [4] Vargas, R. & Bruneau, M. 2006. Seismic design of multi-story buildings with metallic structural fuses. *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, April 18-22, 2006, San Francisco, California, USA. Paper No. 280.
- Inc; pp. 281-304, 1999.