Influence of link length on re-centring capability of dual eccentrically braced frames

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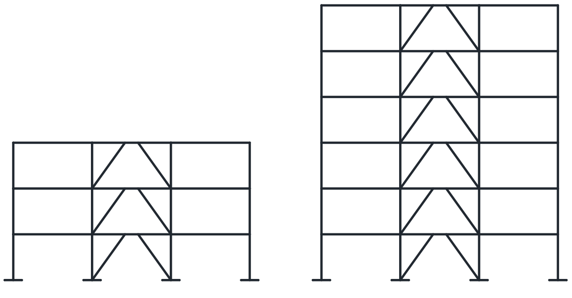
Abstract. Combining steel eccentrically braced frames (EBFs) with removable bolted links with moment resisting frames (MRFs), repair costs and downtime of a structure hit by an earthquake can be reduced, by implementing the concepts of removable dissipative members (bolted links are intended to provide the energy dissipation capacity and to be easily replaceable) and re-centring capability (provided by the more flexible moment resisting frames) in such a dual structure. The seismic performance, re-centring capability and link replacement feasibility of a dual re-centring EBF with removable flush end-plate bolted links were already studied and experimentally validated. In this case, very short links were used in order to achieve the flush end-plate connection over-strength, so it can be kept elastic in order to be able to remove the link. Re-centring capability of EBFs with other types of removable links has not been yet approached. One of the main objectives of an ongoing research project is to extend the validation of re-centring capability and link replacement feasibility on extended end-plate bolted links. This type of connection geometry provides a larger connection capacity, thus short links can be designed longer. The present paper numerically investigates the influence of using different link lengths (and connection detailing) on the re-centring capability of two height levels structures.

1. Introduction

Mankind is more and more concerned lately about the vast amount of material and life loss due to earthquakes. Therefore, structural engineers strive to find solutions that ensure safety without incurring high costs. Eccentrically braced frames are such a solution that ensures a balance between structural stiffness and ductility. In order to reduce costs and downtime of a structure hit by earthquake, the concepts of removable dissipative elements (which ensure energy dissipation capacity and are easily replaceable) and re-centring capability (ensured by the more flexible moment resisting frames) are implemented in a dual structure, obtained by combining eccentrically braced frames (EBFs) with removable links with moment resisting frames (MRFs) [1]. The seismic performance, re-centring capability and link replacement feasibility of a dual re-centring EBF with removable flush end-plate bolted links were experimentally validated within the DUAREM project [2]. In this case, very short links were used in order to achieve the flush end-plate connection over-strength, so it can be kept elastic in order to be able to remove the link. Re-centring capability of EBFs with other types of removable links has not been yet approached. One of the main objectives of an ongoing research project is to extend the validation of re-centring capability and link replacement feasibility on extended end-plate bolted links. This type of connection geometry was previously investigated [3] being proved more rigid than the flush end-plate one and providing a larger connection capacity, thus longer links can be used.

2. Investigated structures

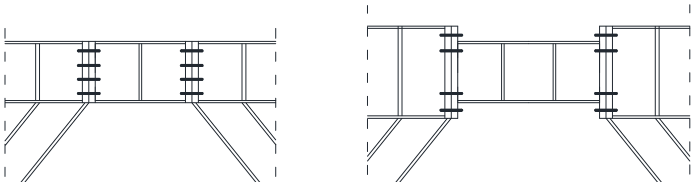
The present paper numerically investigates the influence of using different link lengths (and connection detailing) on the re-centring capability of two height levels structures: low-rise frames with 3 stories (P+2E) and mid-rise frames with 6 stories (P+5E) (Figure 1).



(a) (b)

Figure 1. Elevation of low-rise (a) and mid-rise (b) frames.

Each structure was designed and numerically investigated using two link connection layouts: flush end-plate (F) and extended end-plate (E) (Figure 2).



(a) (b)

Figure 2. Flush end-plate (a) and extended end-plate (b) link connections.

The plan layout of the investigated structures is presented in Figure 3, having three spans of 6 m on one direction and five spans of 6 m on the other direction. The height of each story is of 3.5 m.

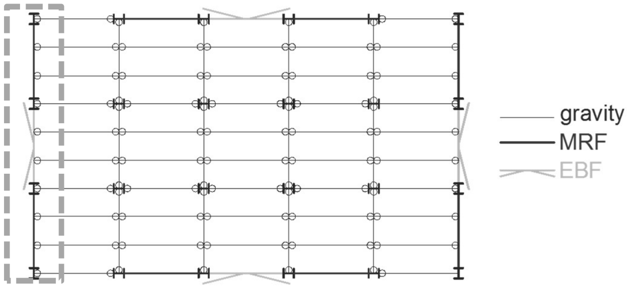


Figure 3. Plan layout of investigated structures.

The main lateral load resisting system is composed of four MRFs and two EBFs on each direction. The marginal frames are dual steel frames that combine two MRFs (ensure the necessary re-centring capability of the structure, providing the restoring forces after an earthquake) with one central EBF with replaceable bolted links (aimed to ensure the energy dissipation and to be easily replaceable) (Figure 1). These are the plane frames that were designed and investigated (Figure 3). All the other inner frames are only gravitational loads resisting frames.

The main beams, columns and braces are made from European I profiles (IPE, HEA, HEB and HEM), and the dissipative bolted links are made from welded I profiles. S355 steel is used for structural elements, as well as S690 high-strength steel in MRFs (in order to ensure the re-centring capability in some cases).

Gravitational loads were considered as uniformly distributed loads on secondary beams and applied as concentrated forces on the main frames. Permanent loads of 5 kN/m^2 were assigned on current floors and 5.5 kN/m^2 on the roof. The live load was considered according to building destination (offices - class B) and partition walls, amounting to 3.8 kN/m^2 for current floors and 3 kN/m^2 on the roof. All gravitational loads assigned to investigated, frames correspond to half the span (3m).

Ductility class high (DCH) was considered, type 1 spectrum, soil type C [4] was used in design, with a peak ground acceleration of 0.3g (Figure 4) and a behaviour factor q=4 was adopted [5].

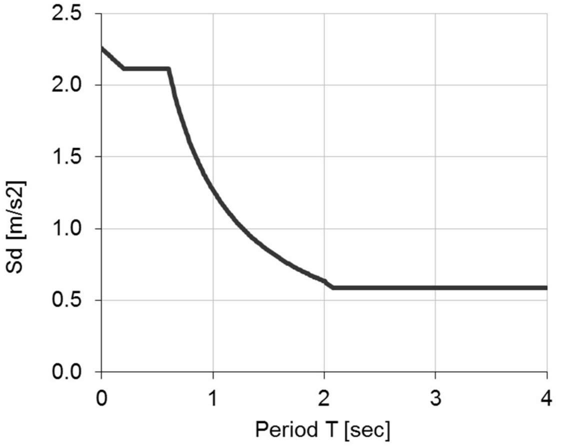


Figure 4. Type 1 spectrum, soil type C.

3. Frames analyses

3.1. Structural analysis

It was not necessary to consider second order effects on any frame. For all frames, the first two modes of vibration have activated 90% of the total mass. Spectral analysis was used to study the structural behaviour.

Replaceable links and MRF beams are the dissipative elements of the frames.

Links must be removable and replaceable. This objective may be attained using a bolted end-plate connection that must be kept elastic. In order to achieve the connection over-strength, short and very short links were adopted (Table 1).

Table 1. Short links

Frame	Limit	Physical length e [m]	Type	Considered over-strength
P+2E_F	$e \approx 0.8\ M_{p,link}/\ V_{p,link}$	0.5	Very short	1.8
P+2E_E	$e \approx 1.6\ M_{p,link}/\ V_{p,link}$	1.0	Short	1.5
P+5E_F	$e \approx 0.8\ M_{p,link}/\ V_{p,link}$	0.8	Very short	1.8
P+5E_E	$e \approx 1.6\ M_{p,link}/\ V_{p,link}$	1.6	Short	1.5

Links were modelled in the global analysis with a reduced equivalent stiffness, to account for the flexibility of the bolted connections.

Frames were designed as dual structures [6]. A structural over-strength of 2.38 (P+2E_F), 2.24 (P+2E_E), 2.57 (P+5E_F) and 2.97 (P+5E_E) was used in the load combination for non-dissipative elements design: columns, braces and EBF beams.

Inter-story drifts were limited to 0.0075h. In order to avoid soft-story mechanisms, "strong column-weak beams" condition was satisfied.

The rigid diaphragm effect was assigned at each level to account for the presence of concrete slabs.

Structural masses were computed from gravitational loads corresponding to half the structure (Figure 5) and assigned to analysed frames nodes, because only the two marginal frames represent the lateral load resisting system.

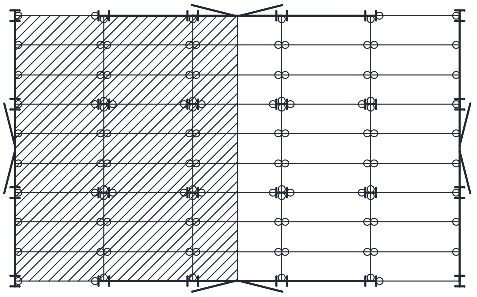


Figure 5. Plan layout of investigated structures.

A leaning (P-Δ) column was used in order to account for the effect of gravitational loads that correspond to the inner frames missing from the 2D analysis (Figure 6).

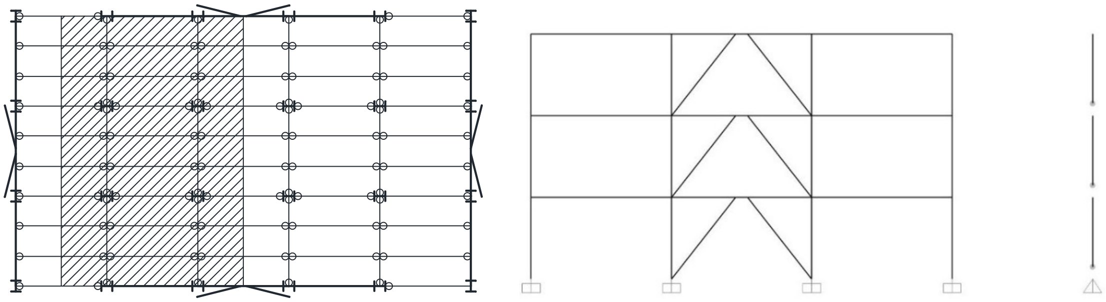


Figure 6. Leaning (P-Δ) column model.

3.2. *Re-centring capability*

A static nonlinear (pushover) analysis was performed in order to check the re-centring capability.

In case of the low-rise building with flush end-plate connections (P+2E_F), yielding was observed outside the links only immediately after reaching 0.14 rad plastic rotation (ultimate deformation capacity at Ultimate Limit State) in these removable elements, the basic design requirement for dual frames with removable links being accomplished. When the peak rotation of a link reaches 0.14 rad (second floor), complete plastic mechanism is attained, with rotations of approximately 0.1 rad in the other links.

Table 2. P+2E_F elements sections

Links (S355)	Central columns (S355)	Corner columns (S355)	Braces (S355)	EBF beams (S355)	MRF beams (S355)
330x200x16x9	HE300B	HE240B	HE260B	HE340A	IPE330
290x190x15x8	HE300B	HE240B	HE240B	HE300A	IPE330
250x180x14x7	HE300B	HE240B	HE200B	HE260A	IPE330

For the other frames (P+2E_E, P+5E_F, P+5E_E), yielding was observed in elements outside links before reaching 0.14 rad in the removable dissipative bars.

In case of the low-rise building with extended end-plate connections (P+2E_E), S690 high-strength steel was used for the re-design of MRFs, thus ensuring frame re-centring (up to the ultimate plastic deformation of 0.14 rad), after eliminating one by one the damaged links. When the peak rotation of a link reaches 0.14 rad (second floor), complete plastic mechanism is attained, with rotations reaching between 0.09 rad and 0.13 rad in the other links.

Table 3. P+2E_E elements sections

Links (S355)	Central columns (S690)	Corner columns (S690)	Braces (S355)	EBF beams (S355)	MRF beams (S690)
330x200x16x9	HE340B	HE240B	HE260B	HE340A	IPE270
290x190x15x8	HE340B	HE240B	HE240B	HE300A	IPE270
250x180x14x7	HE340B	HE240B	HE200B	HE260A	IPE270

In case of the mid-rise building with flush end-plate connections (P+5E_F) , S690 high-strength steel was used for the re-design of MRFs, thus ensuring frame re-centring (up to the ultimate plastic deformation of 0.14 rad), after eliminating one by one the damaged links. When the peak rotation of a link reaches 0.14 rad (third floor), complete plastic mechanism is attained, with rotations reaching between 0.08 rad and 0.13 rad in the other links.

Table 4. P+5E_F elements sections

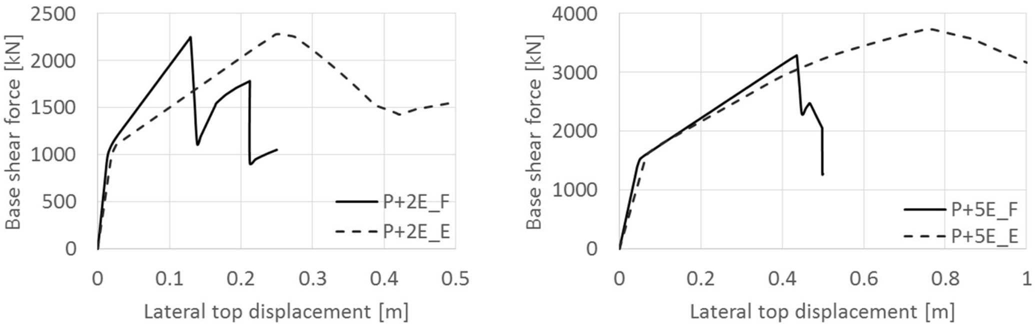
Links (S355)	Central columns (S690)	Corner columns (S690)	Braces (S355)	EBF beams (S355)	MRF beams (S690)
490x240x20x8	HE340M	HE300B	HE320B	HE450A	IPE300
490x240x20x8	HE340M	HE300B	HE320B	HE450A	IPE300
490x240x20x8	HE340M	HE300B	HE320B	HE450A	IPE300
390x240x20x8	HE340B	HE300B	HE280B	HE400A	IPE300
290x240x20x8	HE340B	HE300B	HE260B	HE300A	IPE300
250x190x16x5	HE340B	HE300B	HE200B	HE260A	IPE300

But in case of the mid-rise building with extended end-plate connections (P+5E_E), using S690 steel to re-design the MRFs, ensures frame re-centring only up to reaching 0.07 rad (half the ultimate deformation capacity at ULS) in links, the basic design requirement for dual frames with removable links not being accomplished in this last case.

Table 5. P+5E_E elements sections

Links (S355)	Central columns (S690)	Corner columns (S690)	Braces (S355)	EBF beams (S355)	MRF beams (S690)
490x240x20x8	HE340M	HE300B	HE320B	HE450A	IPE300
490x240x20x8	HE340M	HE300B	HE320B	HE450A	IPE300
490x240x20x8	HE340M	HE300B	HE320B	HE450A	IPE300
390x240x20x8	HE300M	HE300B	HE280B	HE400A	IPE300
290x240x20x8	HE300M	HE300B	HE260B	HE300A	IPE300
250x190x16x5	HE300M	HE300B	HE200B	HE260A	IPE300

Following the conventional elastic design of the four frames, it was observed that adopting extended end-plate connections for the short removable links allows the increase of their lengths, leading to increased frames ductility (Figure 7) and larger lateral drifts, indicating the possibility of adopting a behaviour factor larger than 4, but on the other hand, experiencing extended reinforced concrete slab degradation.



(a) (b)

Figure 7. Investigated low-rise (a) and mid-rise (b) frames behaviour

Using extended end-plate removable short links leads to increased connection design efforts, needing replacement of HEA profiles used for EBF beams, with taller IPE profiles, providing the necessary geometry to achieve the bolted connection.

4. Link removal

For studying the link removal procedure and frame re-centring, a static non-linear "staged construction" analysis was performed on the P+5E_F structure (Figure 8), the procedure being similar also for the other frames.

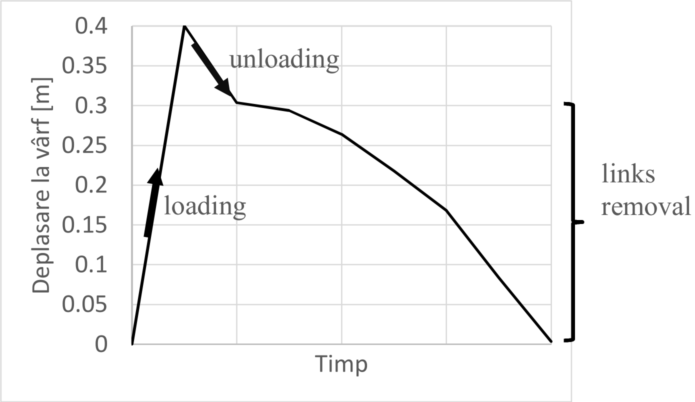


Figure 8. Top displacement during link removal

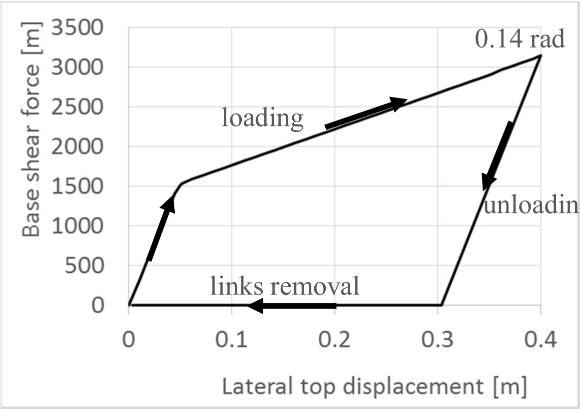


Figure 9. Force-displacement relationship during frame re-centring**.**

The analysis stages are the following: firstly, gravitational loads are applied and lateral forces (until reaching the ultimate plastic deformation of 0.14 rad in links) (Figure 10a), and then the frame is unloaded (Figure 10b), secondly, links are removed story by story, from the bottom one towards the top [7] (Figure 10c-h). After removing the last link, the structure almost recovers its initial position (Figure 9), having a permanent top displacement of 3 mm.

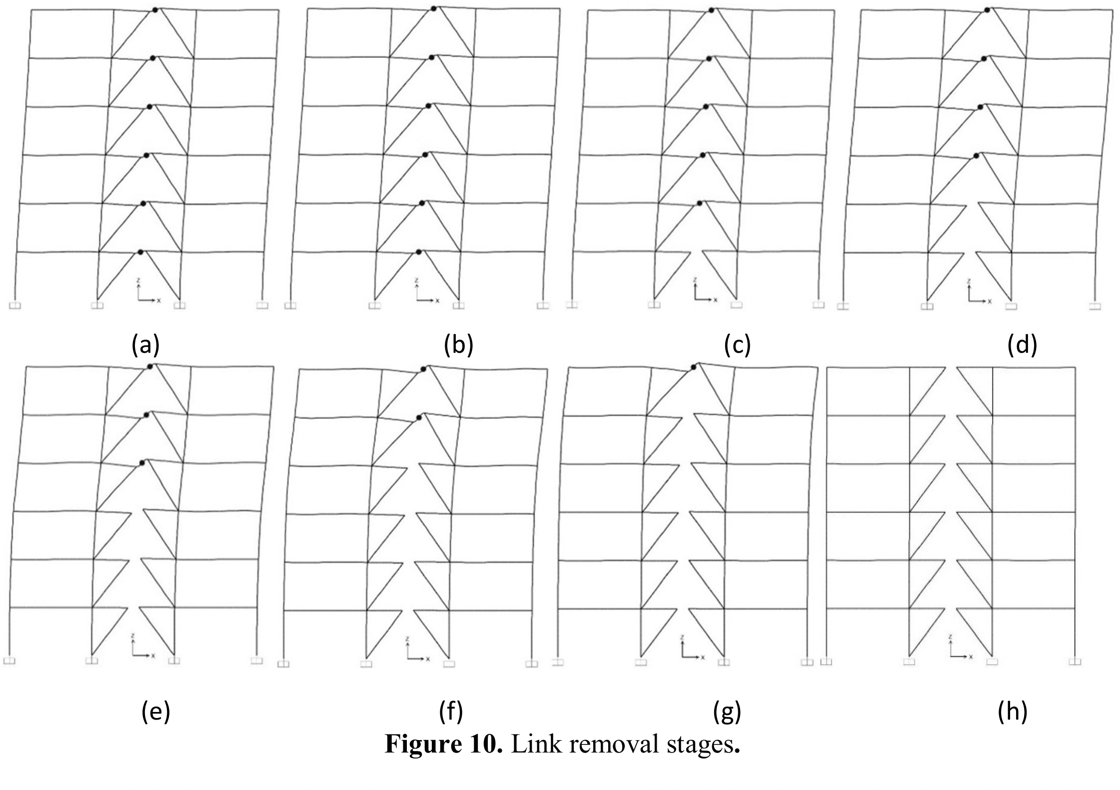


Figure 10. Link removal stages**.**

From technical point of view, the easiest way to remove links is by flame cutting the web and flanges of the bar [8] if large permanent lateral drifts are recorded or by unbolting otherwise, story by story [7], as already proven within the procedure adopted for the experimental specimen of DUAREM project [2].

5. Conclusions

When using flush-end plate connections for the bolted links in dual EBFs with re-centring capability, very short lengths (e $\leq 0.8\ M_{p,link}/\ V_{p,link}$) are necessary in order to provide the connection capacity within the given geometry. This leads to less ductile frames and larger links over-strength, but ensures the re-centring capacity up to the ultimate plastic rotation in links at ULS (MRFs providing the necessary restoring forces by remaining elastic, plastic deformations being constrained in links only).

The removable shear links could also be designed longer (e $\leq 1.6\ M_{p,link}/\ V_{p,link}$), but by adopting extended end-plate connections in order to provide the connection capacity within the given geometry. This leads to a larger frame ductility (indicating the possibility of using larger behaviour factors) and smaller links over-strength, but ensures the re-centring capacity only for low-rise frames (and by using high-strength steel in MRFs). In case of mid-rise (and taller) frames, the MRFs are not able to provide the necessary restoring forces (even if high-strength steel is adopted), as they yield before ultimate plastic rotation is attained in links.

6. References

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