Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Morfuni, F., **Freddi, F.,** Galasso, C.
University College London, Chadwick Building
Department of Civil, Environmental & Geomatic Engineering (CEGE)
e-mail: **f.freddi@ucl.ac.uk**

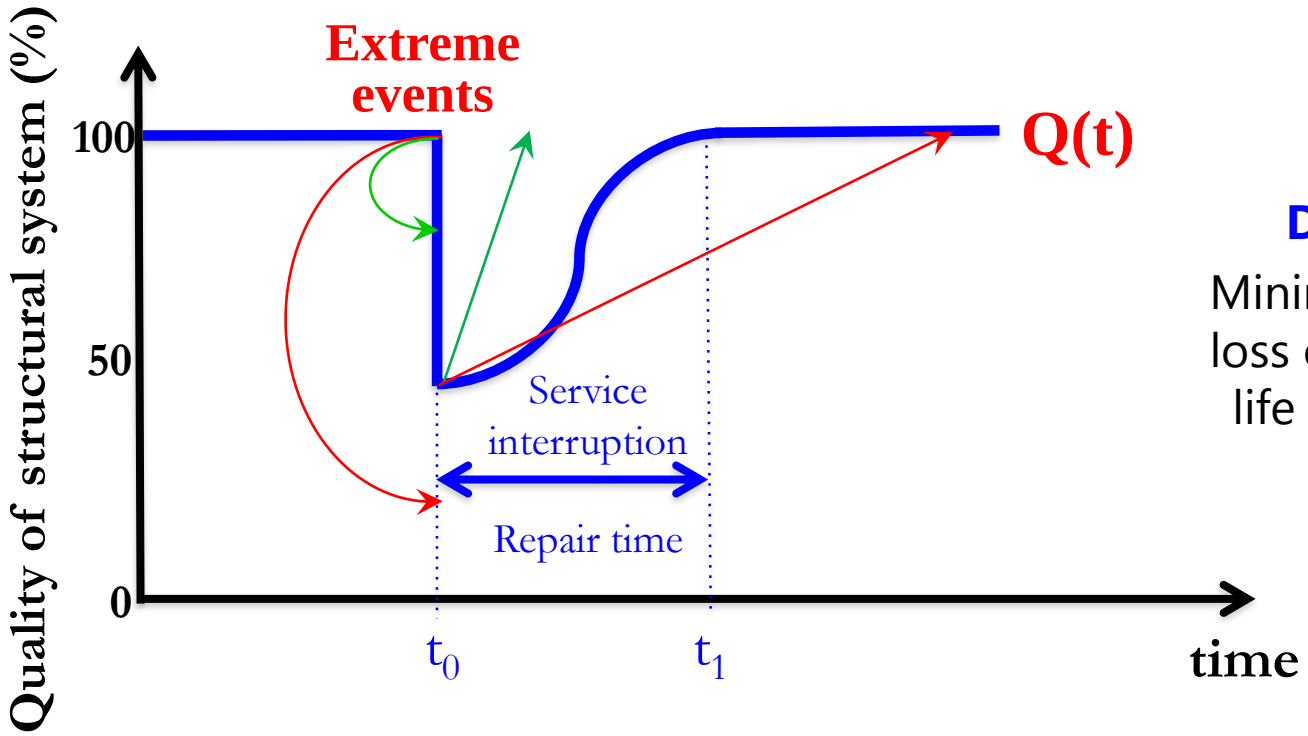
UCL ENGINEERING
Change the world

EPICentre

CEGE DEPARTMENT OF CIVIL, ENVIRONMENTAL & GEOMATIC ENGINEERING 190 YEARS
ENGINEERING A BETTER WORLD

Resilience

Defined as the capability of a structure to return to functionality (i.e. 100% quality) within an acceptable short, if not immediate time.



Design objective

Minimise repair time and loss of service during the life span of a structural system

t_o: Occurrence of extreme event

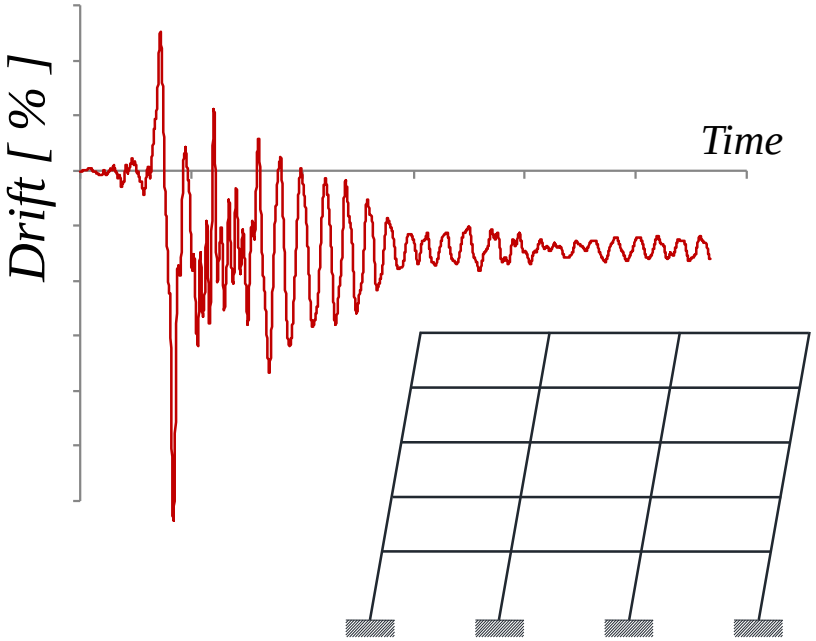
t_o: Detection of severe deterioration

Loss of Resilience in practice…

t_o: Extreme event

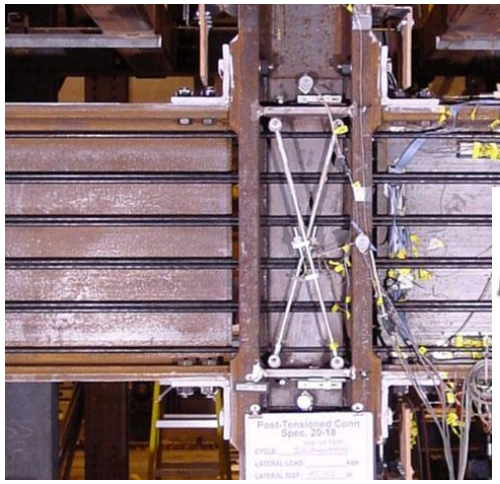
Inelastic deformations and damage in structural members

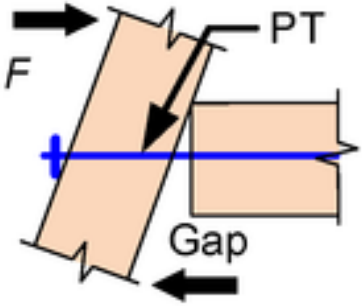
Residual story drifts



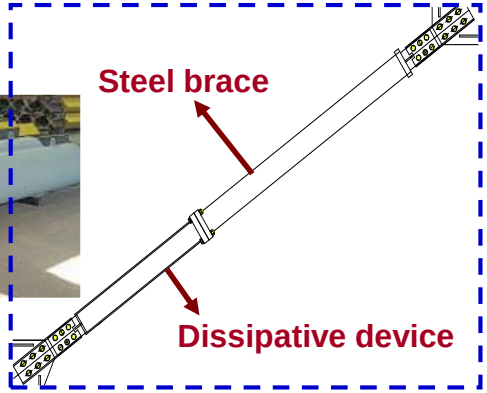
Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Self-centering Beam-Column Connections

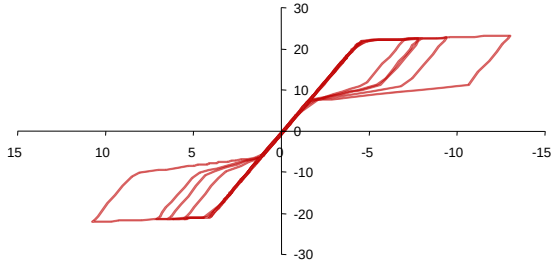




Passive Energy dissipation Devices



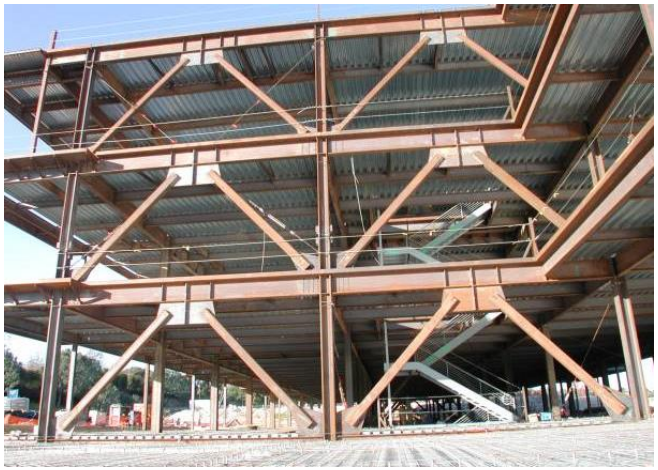
Shape Memory Alloys (SMA)

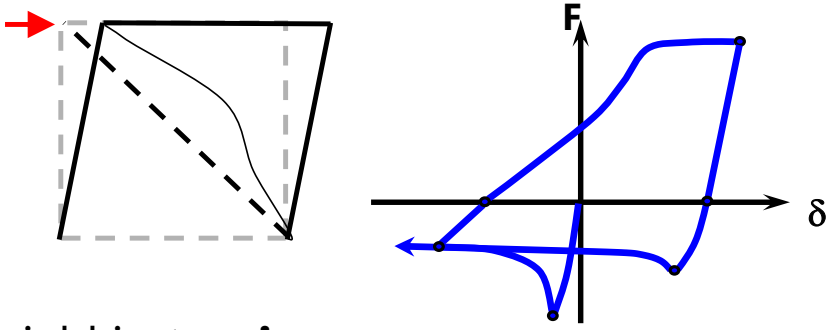


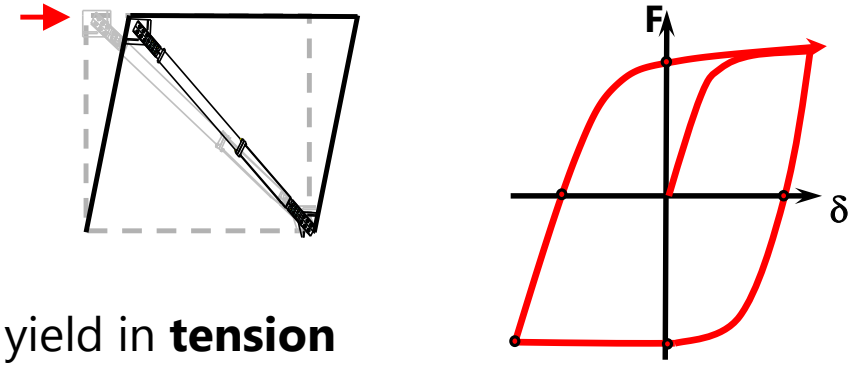
Tuned Mass Dampers (Taipei 101)

Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

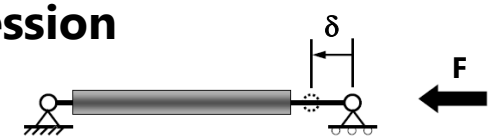
Concentric Braces Vs Buckling-Restrained Braces (BRBs)







- yield in **tension**
- buckle in **compression**

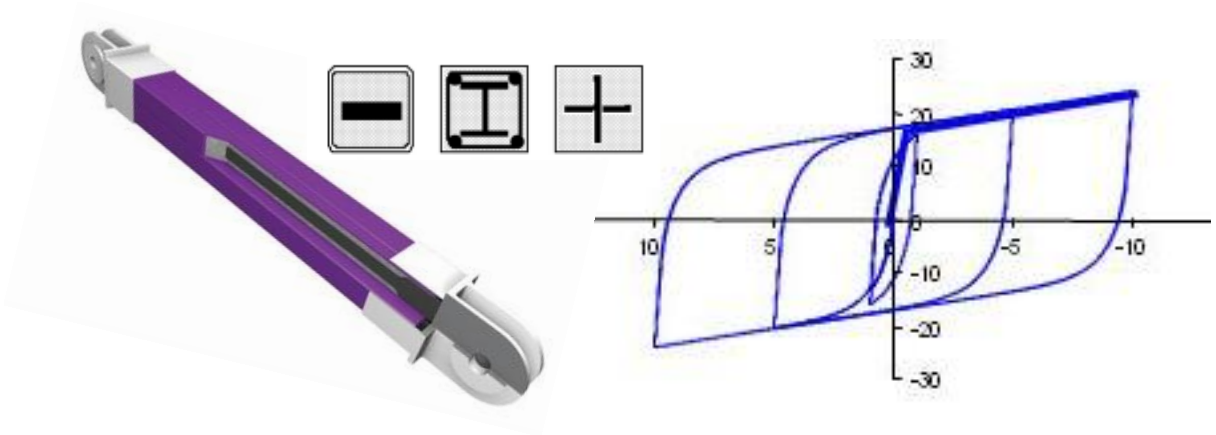


- yield in **tension**
- yield in **compression**
- **similar** tension/compression **strengths**

Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Buckling-Restrained Braces (BRBs)

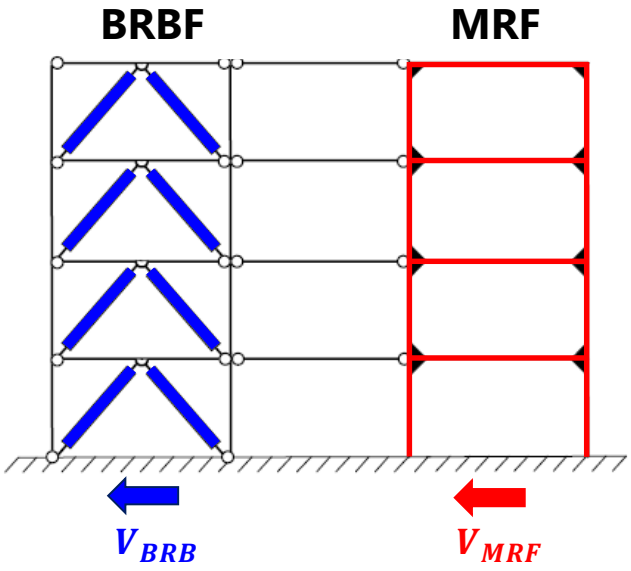
In BRBs, a **sleeve provides buckling resistance to an unbonded core that resists the axial stress**. As buckling is prevented, BRBs behave in a similar way in tension and in compression allowing for the development of stable hysteretic cycles, providing significant energy dissipation capacity.



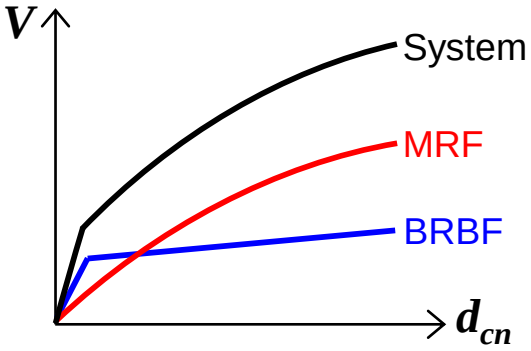
- High initial stiffness
- Low hardening
- Large ductility capacity

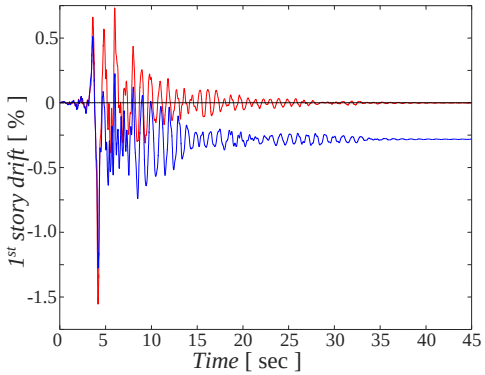
- provide **strength** and **stiffness** to buildings
- provide **large** and **stable energy dissipation capacity**
- can lead to **large residual drifts** (low hardening)
- suffer from **cumulative damage** (MS-AS sequences)

Dual Systems with MRFs and BRBs



- BRBs for stiffness and strength;
- BRBs for energy dissipation (**replaceable fuses**)
- Back-up MRF (**self-centring capability**)
- MRF for redistribution of lateral forces (**no soft-storey**)

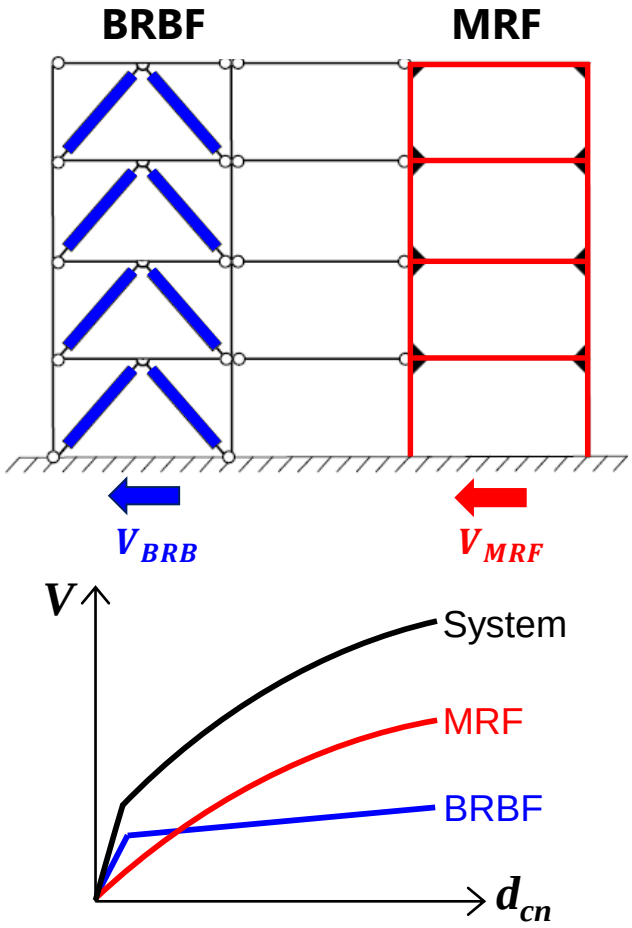




Tubaldi, E., Freddi, F., Zona, A., Dall'Asta, A. (2018). "Seismic Performance of Steel Dual Systems with BRBs and Moment-Resisting Frames", *16th European Conference on Earthquake Engineering*, 18-21 June 2018, Thessaloniki, Greece.

Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Dual Systems with MRFs and BRBs



- BRBs for stiffness and strength;
- BRBs for energy dissipation (**replaceable fuses**)
- Back-up MRF (**self-centring capability**)
- MRF for redistribution of lateral forces (**no soft-storey**)

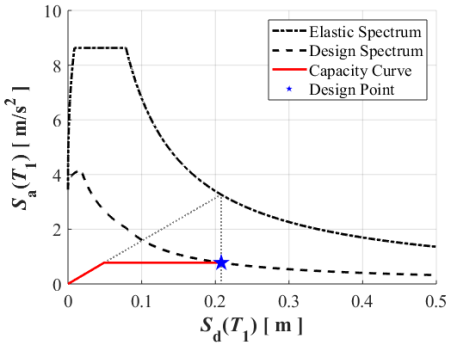
Same Challenges

- Uncertainty in the devices properties (Force ±15%)
- Uncertainty in the device capacity (max and cumulative ductility)
- No safety coefficients for the design of dissipative devices
- Lack of code-design recommendations for dual frames

Tubaldi, E., Freddi, F., Zona, A., Dall'Asta, A. (2018). "Seismic Performance of Steel Dual Systems with BRBs and Moment-Resisting Frames", *16th European Conference on Earthquake Engineering*, 18-21 June 2018, Thessaloniki, Greece.

Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Dual Systems Design Procedure (Displacement Based Design)



Seismic demand in acceleration-displacement format

↓

Definition of μ_{MRF}, θ_d and $\alpha = \frac{V_{BRB}}{V_{MRF}}$

↓

Deformed shape based on the DBD approach

↓

First choice of μ_{BRB} and V_{base}

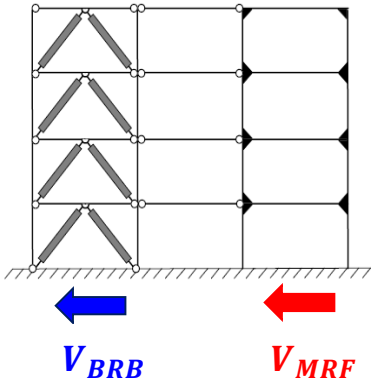
↓

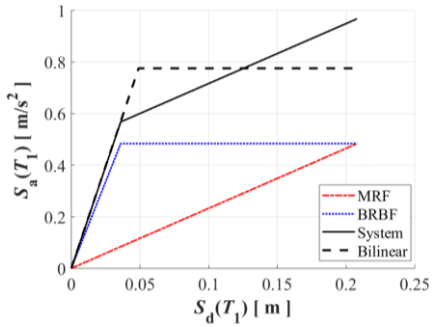
Compliance with the N2 method?

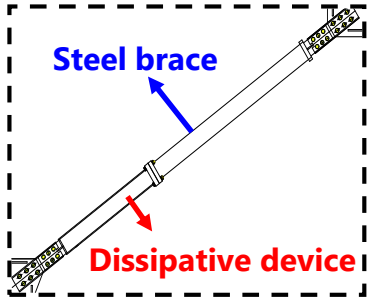
No → **Iteration** → First choice of μ_{BRB} and V_{base}

Yes ↓

Elements sized to meet local stiffness, strength and ductility requirements





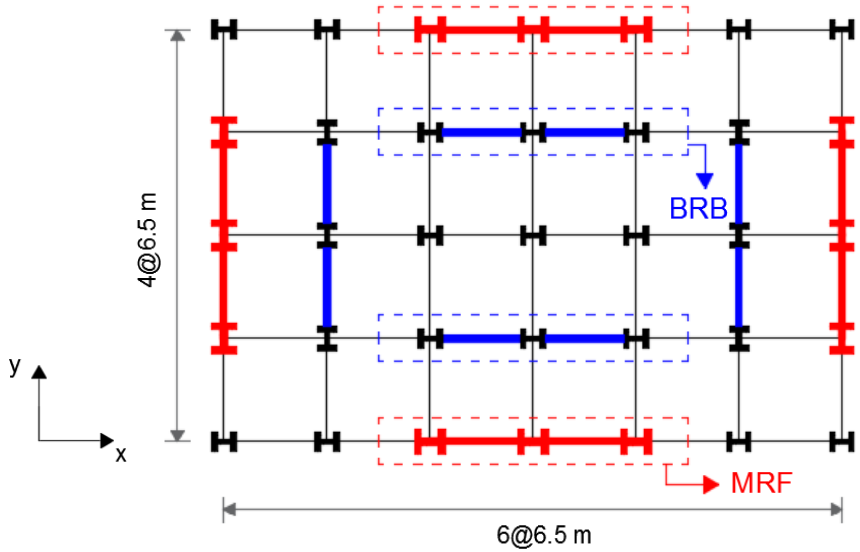


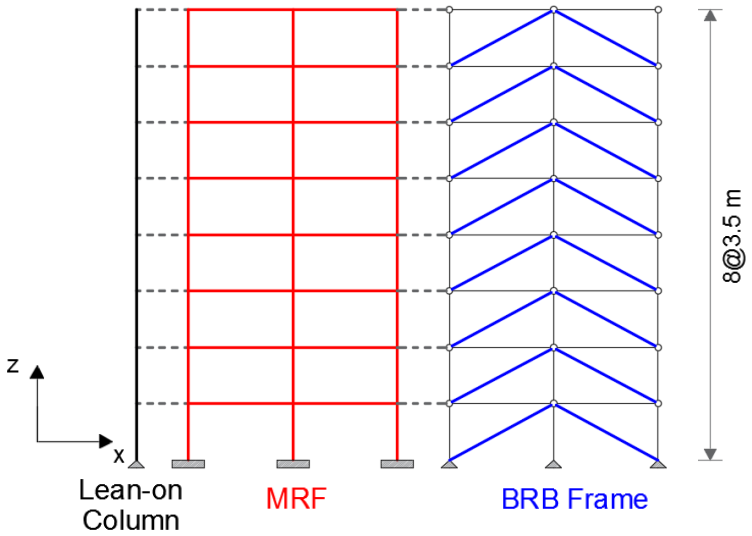
1. **Same mode shape (K_i)**
2. **Simultaneous yielding (F_{yi})**

Maley, T.J., Sullivan, T.J., Della Corte, G. (2010). "Development of a Displacement-Based Design Method for Steel Dual Systems with Buckling-Restrained Braces and Moment-Resisting Frames", *Journal of Earthquake Engineering*, 14(S1), 106-140.

Case Study Structure

(8-storey, 6 by 4 bays building in Italy $a_{gR} = 0.26g$)



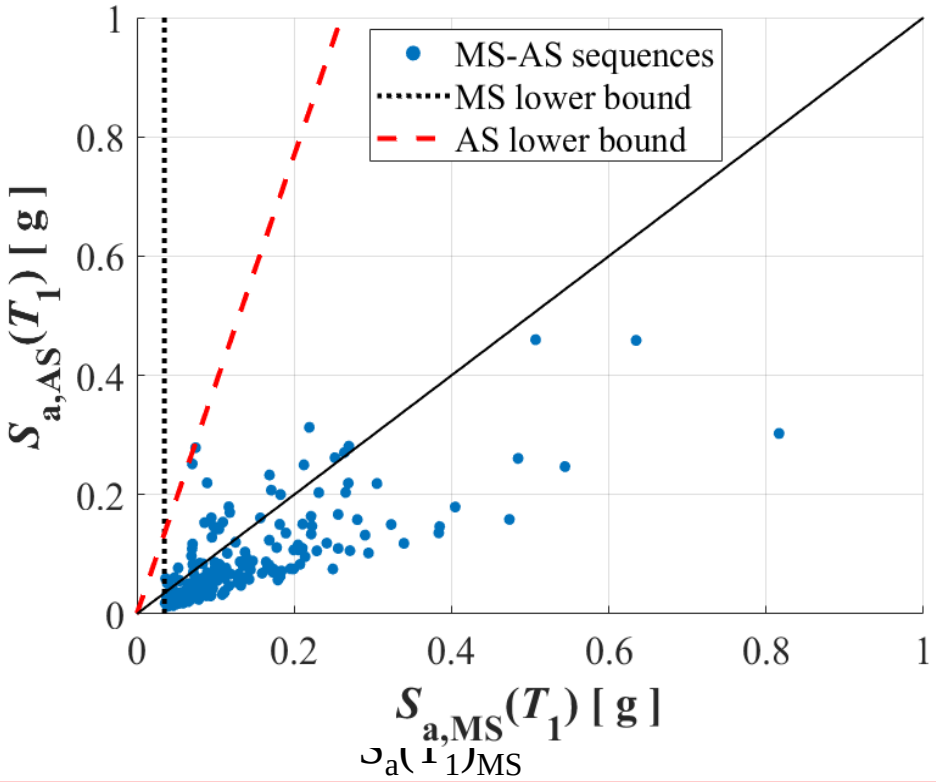


- Plane frame
- Fiber sections for columns (N-M interaction)
- Lumped plasticity approach for beams
- Zero length rotational springs for plastic hinges (Ibarra-Medina-Krawinkler)
- Kinematics of panel zones (Scissor model, Finley et al. 2004)
- Refined BRB models (Zona and Dall'Asta 2012)
- Lean-on column (P-Δ effects)

MS-AS ground motion sequences selection

703 MS-AS sequences (from Goda & Taylor 2012) from 2012 KKiKSK (K-NET/KiK-net) and NGA-W

- Only crustal ea … e location (i.e., Italy)
- Disregard sequ … intensity
- Disregard sequ … design intensity
- Disregard sequ …



Subset of 199 MS-AS sequences

Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

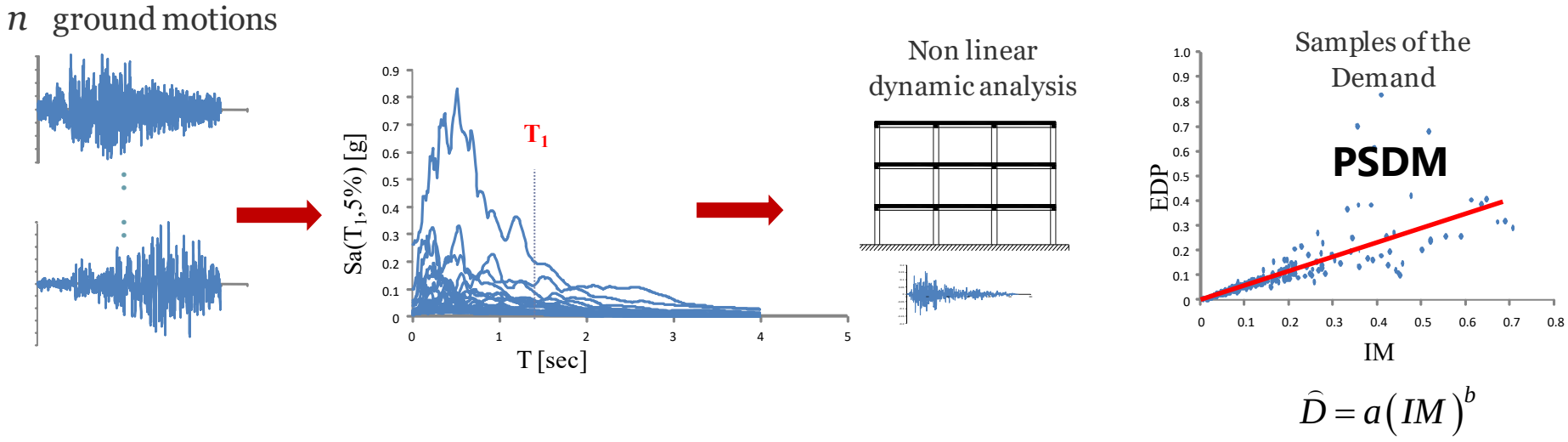
Fragility Definition

- $S_a(T_1)$ as **IM**
- MRF remain elastic
- BRBF failure due to:
  - Maximum ductility (μ)
  - Cumulative ductility (μ_{cumul})

Assumed Capacity Values (Collapse only)

EDPs (25) (400)

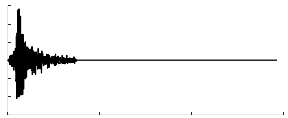
- Cloud Analysis

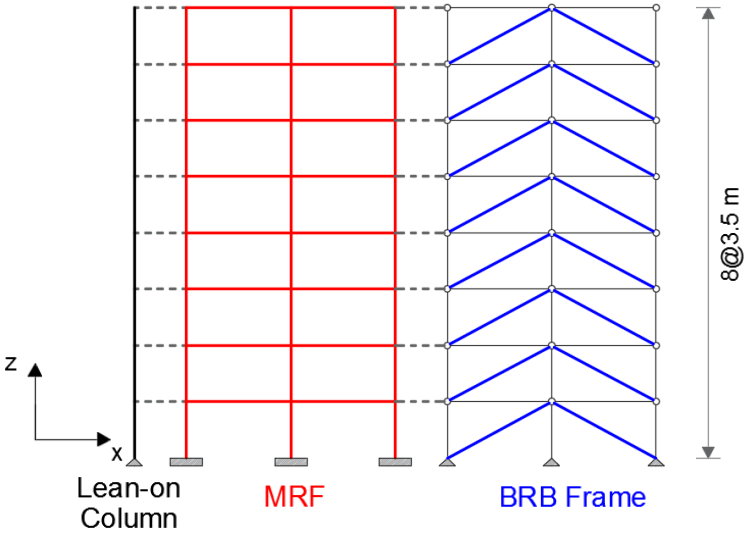


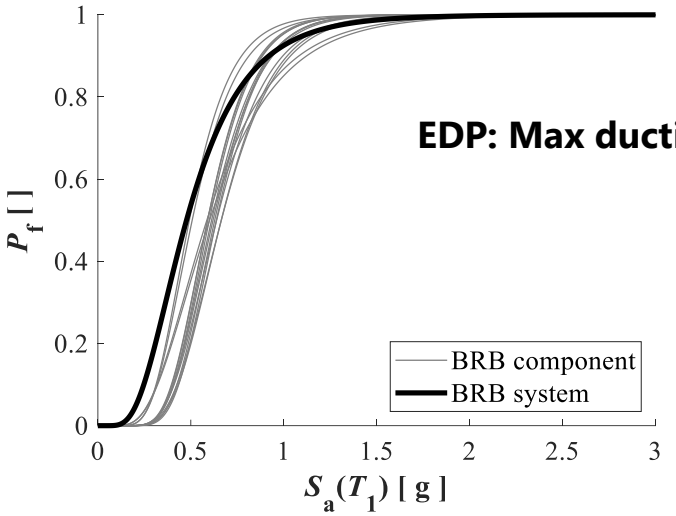
$$\hat{D} = a(IM)^b$$

Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Undamaged Structure – MSs only

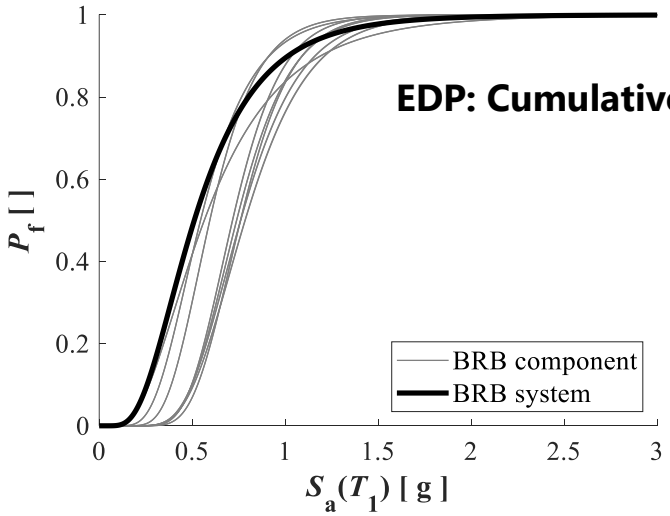






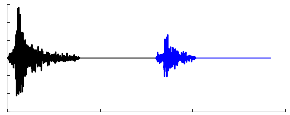
Similar components' performance (Design Method)

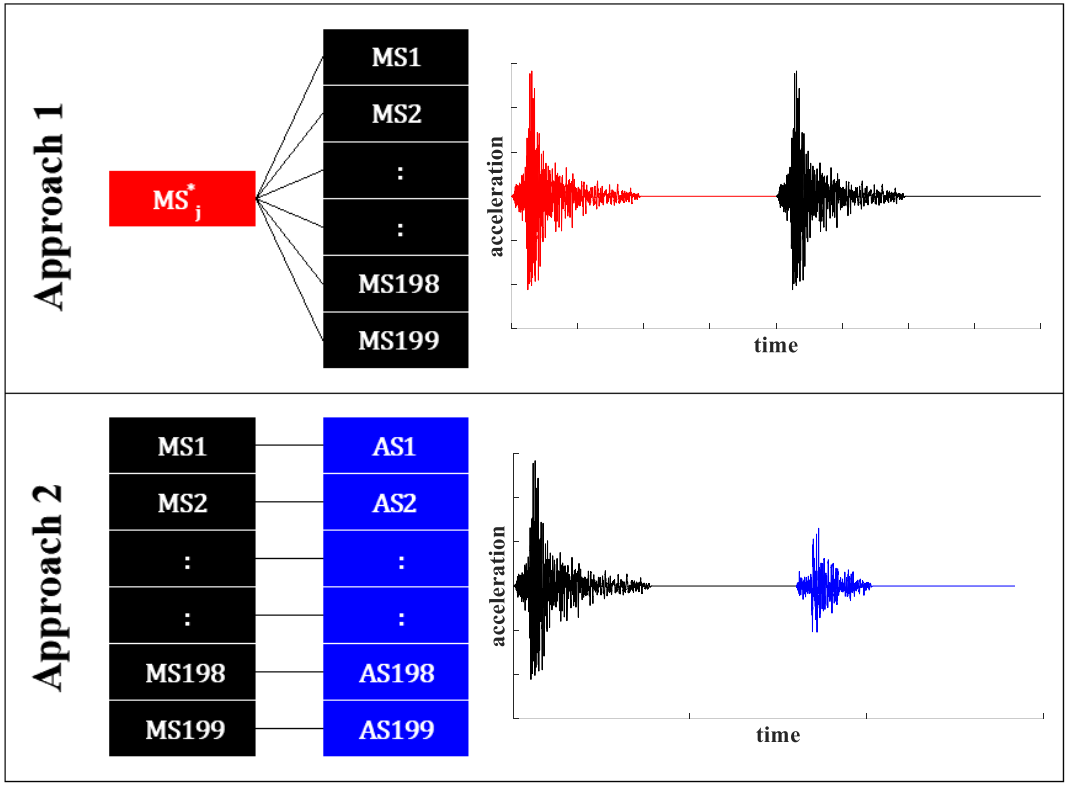
System fragility curves based on a series arrangement



Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Damaged Structure – MS-AS sequences



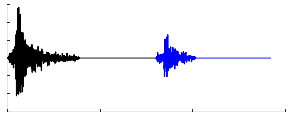


Artificial MS-AS sequences. (Back-to-back)
(Effect of damage accumulation)

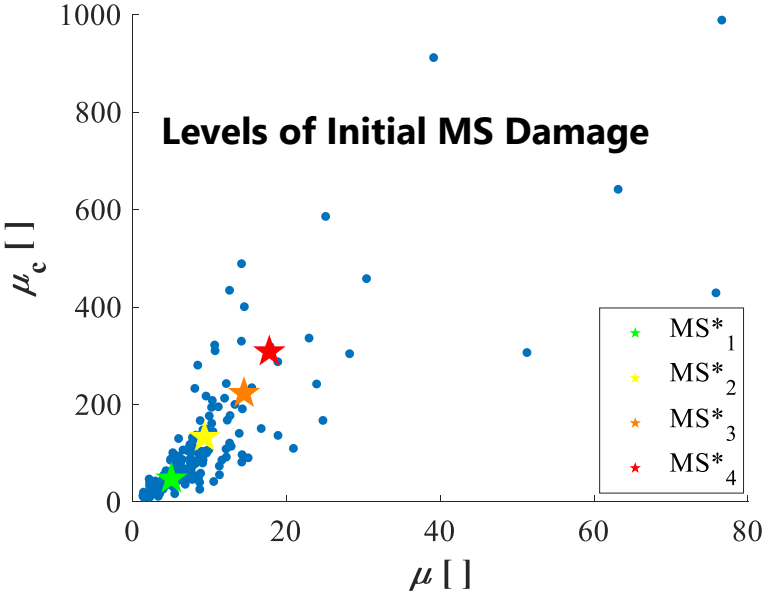
Natural MS-AS sequences.
(potential of the AS to induce additional damage)

Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

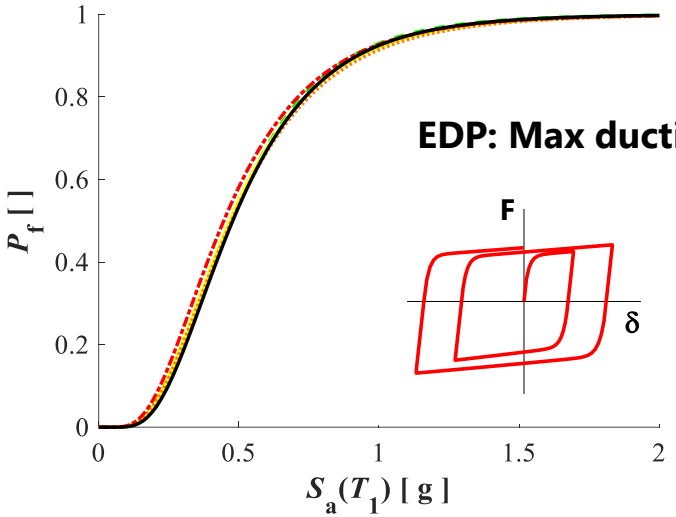
Damaged Structure – Approach 1



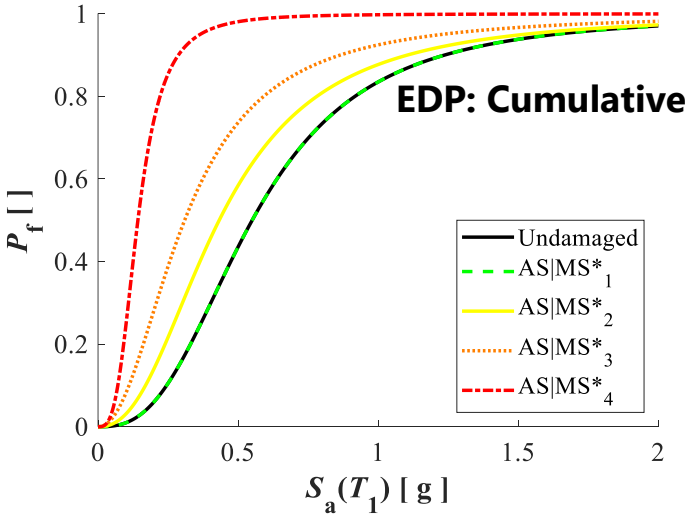
μ and μ_c demand values distribution



4 MSs selected corresponding to the 20, 40, 60 and 80% of the capacity limit for both the EDPs



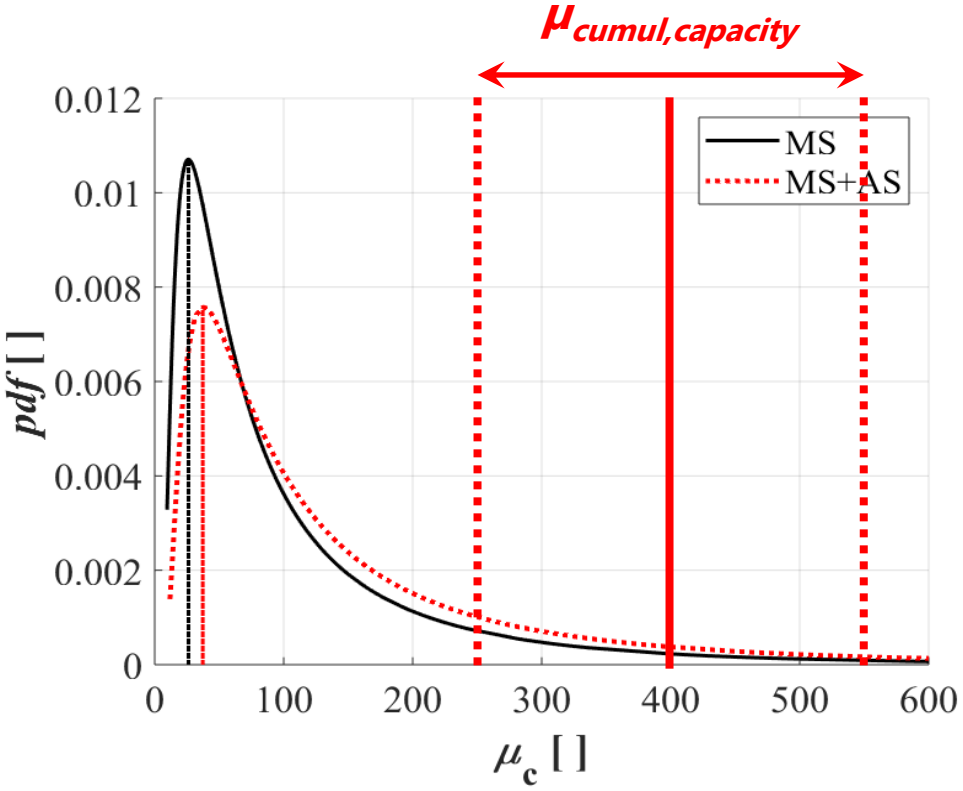
Stable cyclic behavior of the BRB



Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Damaged Structure – Approach 2

Approach 1 neglects the statistical correlation that exists between MS and AS



- pdf for μ_{cumul} for the undamaged (MS events only) and damaged structure (real MS-AS sequences).
- Negligible variation in the mean values.
- This preliminary result shows that real AS sequences are not expected to significantly increase the μ_{cumul} demand.

1. One single aftershock…

2. Large uncertainty in the cumulative ductility capacity…

Morfuni, F., **Freddi, F.,** Galasso, C. (2019) Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences

Conclusions ...some answers...

- To address the **drawbacks of conventional BRB frames**, an **optimal displacement-based design method** for **dual (MRF-BRBF) systems** has been investigated and applied to a 8-storey case study building;
- The seismic performance of the prototype structure has been assessed by means of **sequential Cloud Analysis**, accounting for potential cumulative damage;
- Results show that the **resilience** of newly-designed dual systems can be achieved by combining elastic re-centring back-up MRFs in parallel with dissipative BRB frames.

Open Questions / Future work

- Multiple AS seismic sequences...
- BRBs replacements after the seismic sequence...
- MRF properties for self-centering... How strong ($V_{b,MRF}$)?
- Safety coefficients for dissipative devices (i.e., BRBs)?
- Code recommendations....

Thank you for your attention

Morfuni, F., **Freddi, F.,** Galasso, C.
University College London, Chadwick Building
Department of Civil, Environmental & Geomatic Engineering
e-mail: **f.freddi@ucl.ac.uk**

UCL ENGINEERING Change the world

EPICentre

CEGE DEPARTMENT OF CIVIL, ENVIRONMENTAL & GEOMATIC ENGINEERING 190 YEARS ENGINEERING A BETTER WORLD