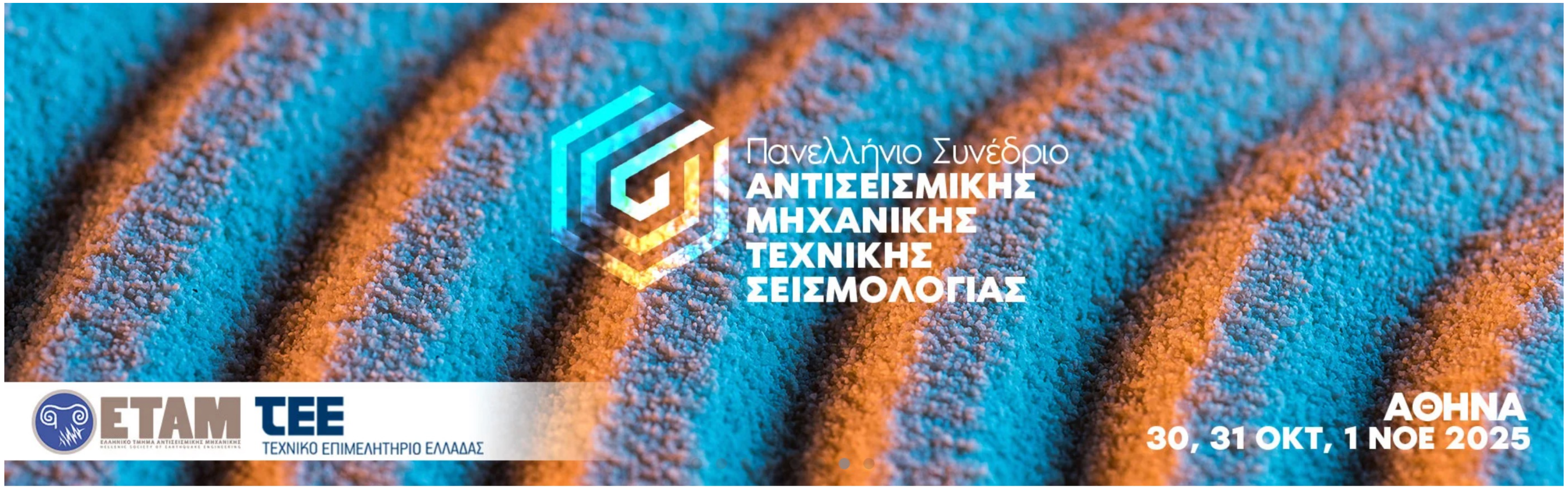
Seismic behaviour of composite-steel moment frames: Experiments, Models and Contributions to new Eurocode 8



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- Dr. Hiroyuki Inamasu, PhD EPFL, 2021

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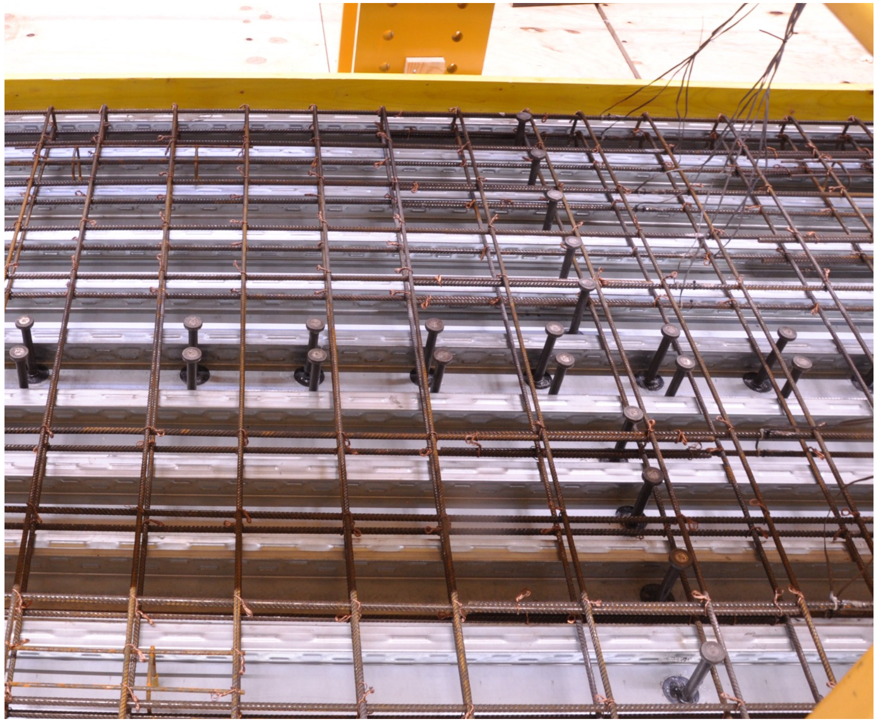
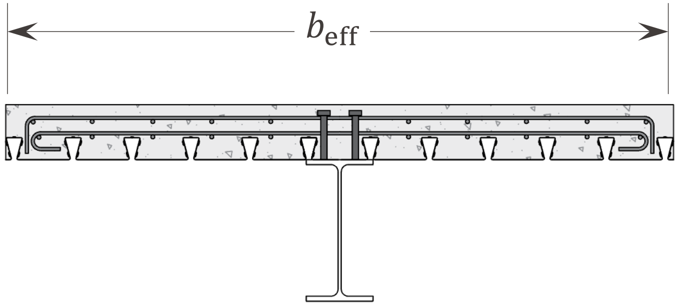
Motivation: Composite steel moment resisting frames



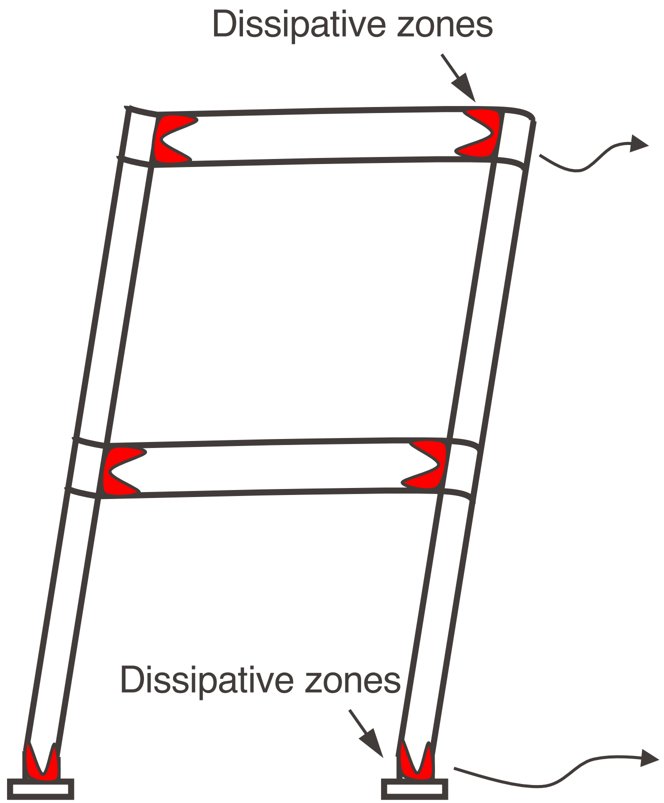
Images courtesy of D. Lignos

- Enhanced lateral stiffness and strength due to composite action
- Potentially lighter steel designs for higher degrees of composite action

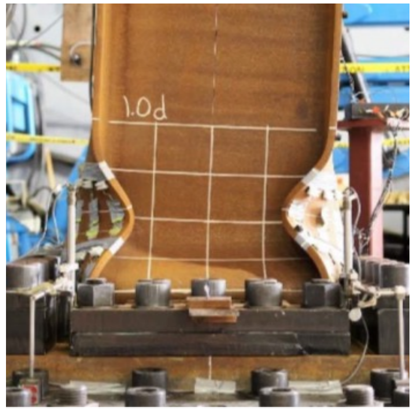
Motivation: What is the ‘right’ effective width?



Code	Effective width*	
	Interior column	Exterior column
CEN (2004a)	$\min\begin{cases}0.075l \\ e\end{cases}$	(1) $\min\begin{cases}0.075l \\ e\end{cases}$ (2) $\min\begin{cases}0.5(b_c+0.7h_c) \\ e\end{cases}$ (3) $\min\begin{cases}0.5(b_c'+0.7h_c) \\ 0.05l \\ e\end{cases}$
AISC (2016a)	$\min\begin{cases}0.0125l \\ w \\ e\end{cases}$	
AIJ (2010a)	b_b	



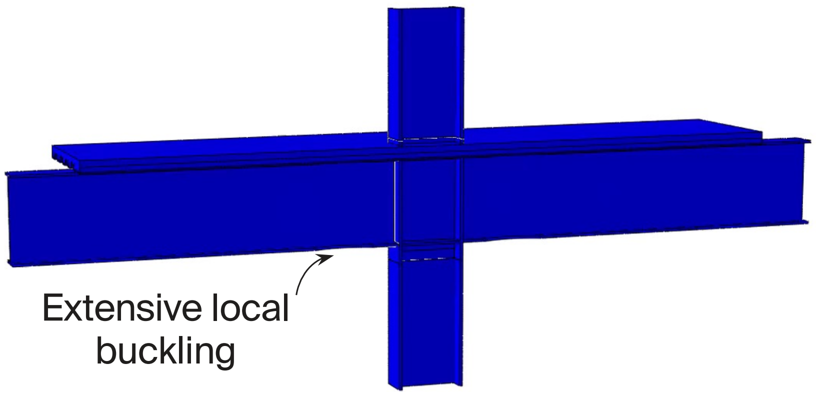
(El Jisr and Lignos, 2019)



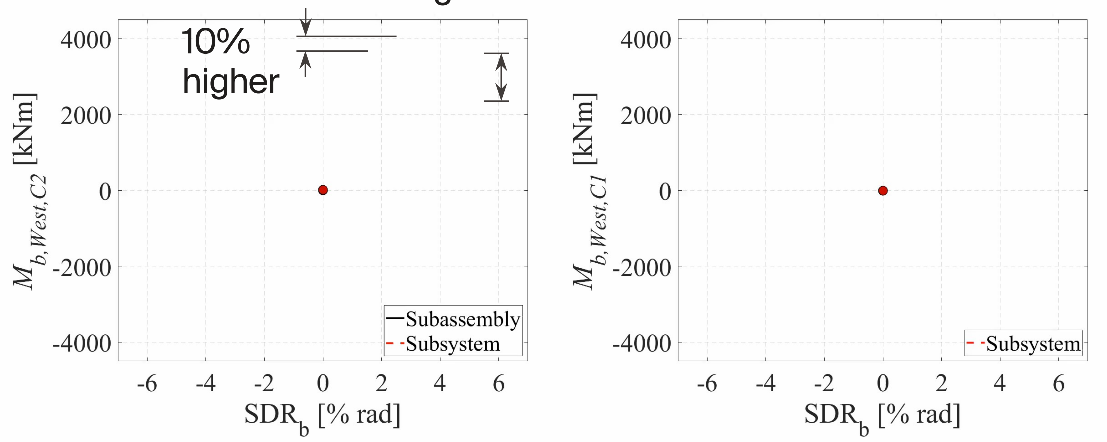
Elkady and Lignos (2018)

Effects of slab restraint and framing action

Subassembly versus system-level behaviour

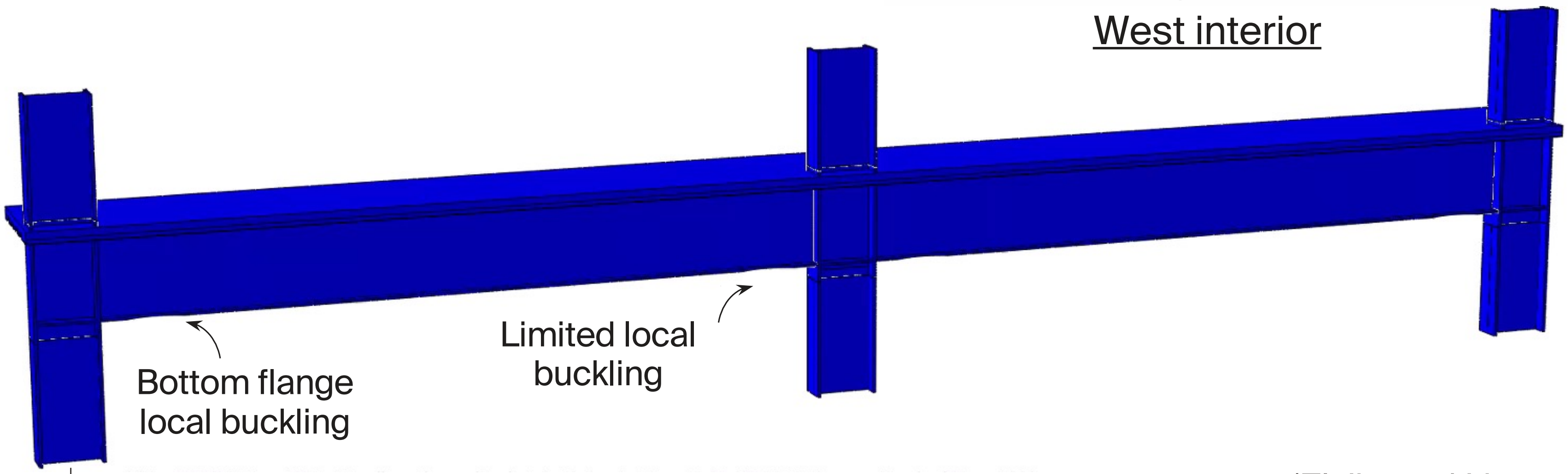


25% lower flexural strength degradation



West interior

West exterior



(El Jisr and Lignos, 2021)

Motivation: Resistance of shear connectors

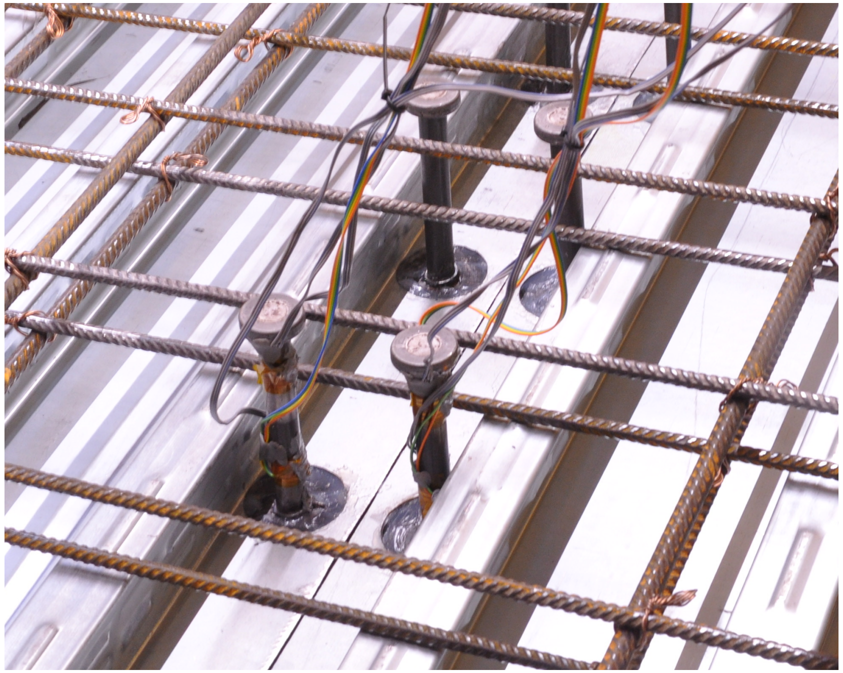
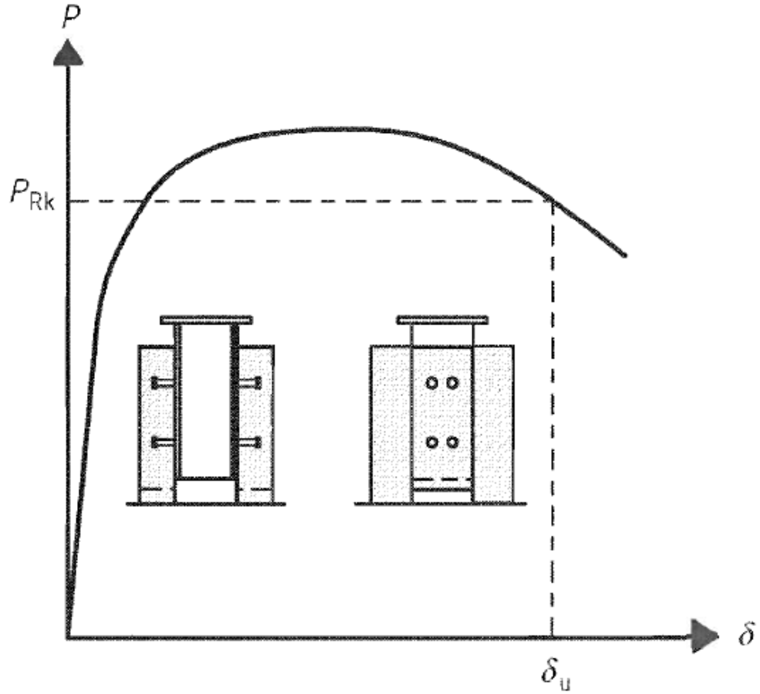


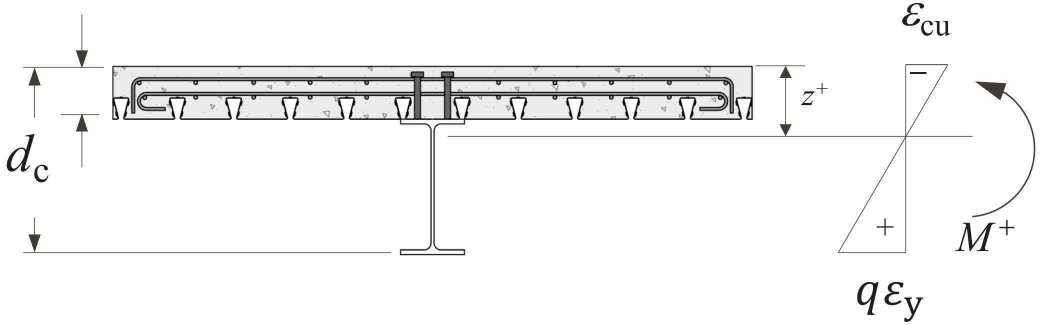
Image courtesy of Prof. D. Lignos



Source: EN 1994-1-1 Annex D (2004)

- In seismic applications: additional 25% reduction <u>regardless of the beam depth</u>
- Headed shear connectors to be ductile ($h_D \geq 4d$)
- Deformability $\delta_{\mathrm{u}} \geq 6mm$

Motivation: Ductility requirements for composite steel beams



$$\frac{z^+}{d_c} \leq \frac{\varepsilon_{cu}}{\varepsilon_{cu} + q \cdot \varepsilon_y}$$

- In EN1998-1-1:2004, $\varepsilon_{cu} = 2{,}5‰$

EN1998-1:2004 (Chapter 11)

Not allowed

Fully Composite Beam										
	L [mm]	z/d								Limit
q		IPE270	IPE300	IPE330	IPE360	IPE400	IPE450	IPE500	IPE550	
1.5	5000	0.336	0.317	0.315	0.345	0.387	0.414	0.439	0.457	0.50
	6000	0.332	0.313	0.297	0.284	0.332	0.368	0.400	0.424	0.50
	7000	0.327	0.309	0.294	0.281	0.277	0.323	0.361	0.391	0.50
	8000	0.322	0.305	0.290	0.278	0.262	0.277	0.322	0.358	0.50
	9000	0.318	0.301	0.287	0.275	0.259	0.242	0.284	0.325	0.50
2	5000	0.336	0.317	0.315	0.345	0.387	0.414	0.439	0.457	0.43
	6000	0.332	0.313	0.297	0.284	0.332	0.368	0.400	0.424	0.43
	7000	0.327	0.309	0.294	0.281	0.277	0.323	0.361	0.391	0.43
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	6000	0.332	0.313	0.297	0.284	0.332	0.368	0.400	0.424	0.21
	7000	0.327	0.309	0.294	0.281	0.277	0.323	0.361	0.391	0.21
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6.5	5000	0.336	0.317	0.315	0.345	0.387	0.414	0.439	0.457	0.19
	6000	0.332	0.313	0.297	0.284	0.332	0.368	0.400	0.424	0.19
	7000	0.327	0.309	0.294	0.281	0.277	0.323	0.361	0.391	0.19
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	9000	0.318	0.301	0.287	0.275	0.259	0.242	0.284	0.325	0.19

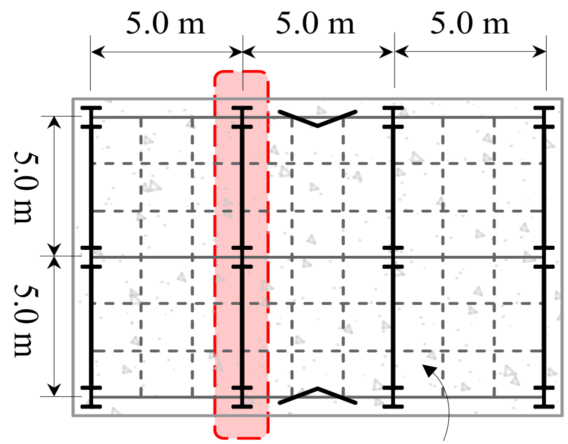
- Very restrictive for seismic designs of composite steel MRFs with $q > 2{,}0$

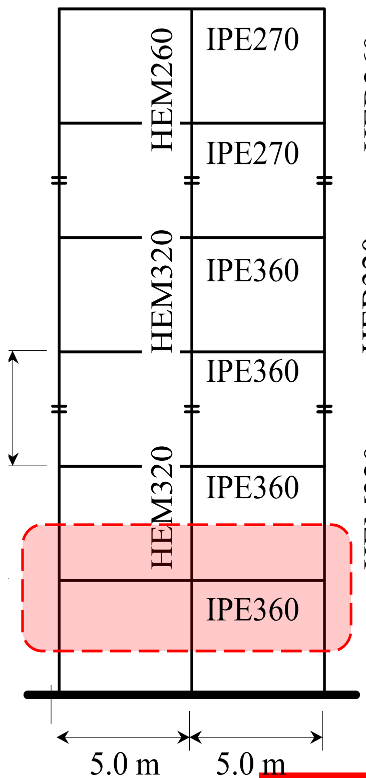
Objectives

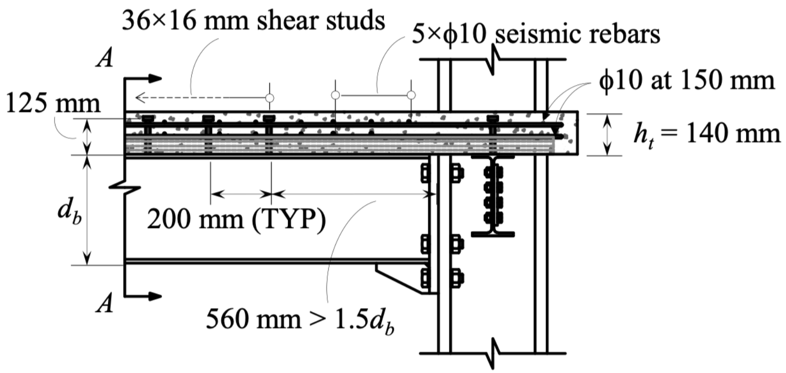
- Full-scale experiments (members & systems) to comprehend the role of the slab on seismic stability of composite-steel MRFs
- Develop standardized models for seismic assessment of composite-steel MRFs
- System-level studies to benchmark the collapse risk of composite-steel MRFs (Ductility Class 2 in EN1998-1-2:2025)
- Improve the seismic design provisions for composite-steel/steel MRFs (new Chapters 11 & 12 in EN1998-1-2:2025):
  - Effective width of composite steel beams
  - Shear resistance & ductility of shear connectors (beams with $d \leq 500mm$)
  - Seismic stability of steel columns

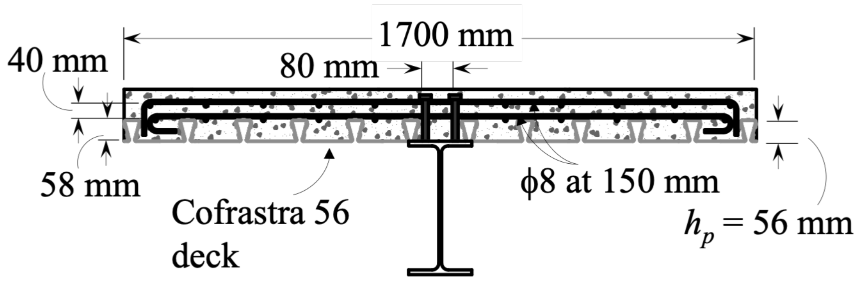
EPFL Overview of prototype building

- 2-bay composite-steel MRF (S355J2 steel, C25)
- Site Class D, a_g=0.22g
- Design location: Sion (CH), Katerini (GR), Rimini (IT)
- Degree of composite action, $n \sim 60\%$ (partial slip)
- Assumed behaviour factor, $q = 3{,}0$ (DC2 in EN1998-1-2:2025)
- Stiffened end-plate beam-to-column connections
  - Fabrication: EXC2 according to EN1090-2





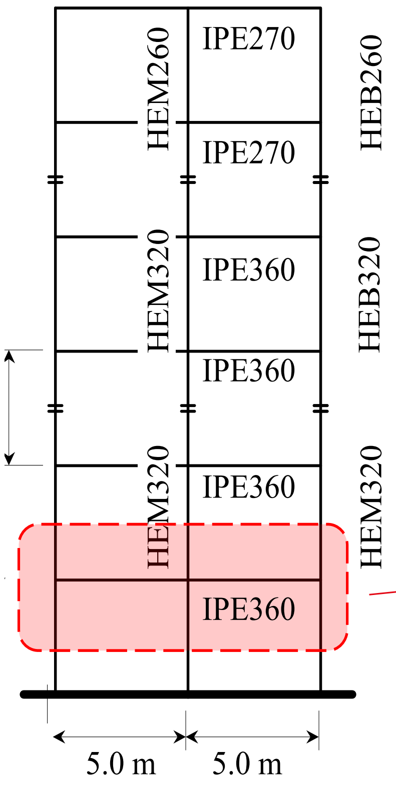


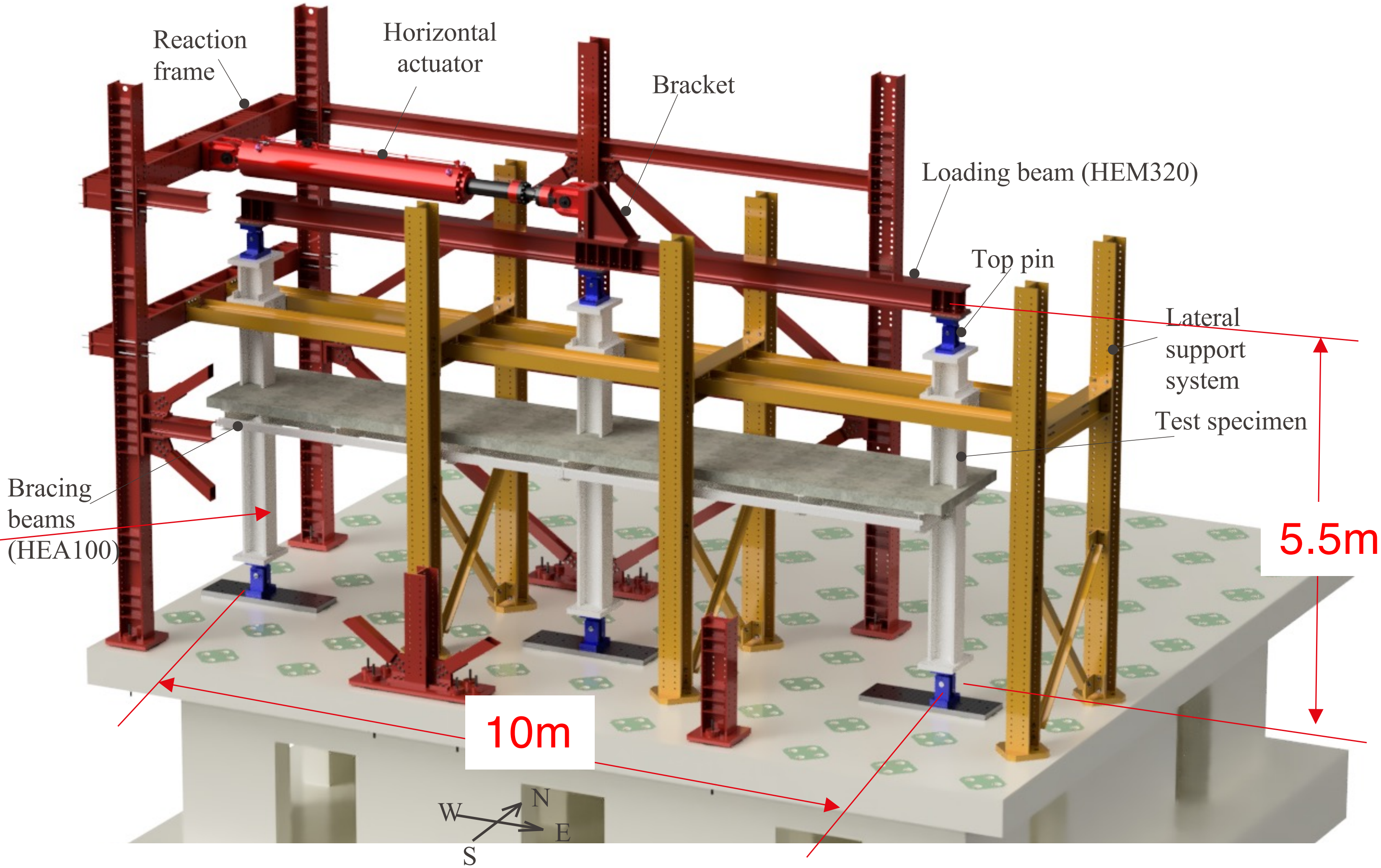


SEC *A-A*

Test structure

2500kN / 2400mm stroke



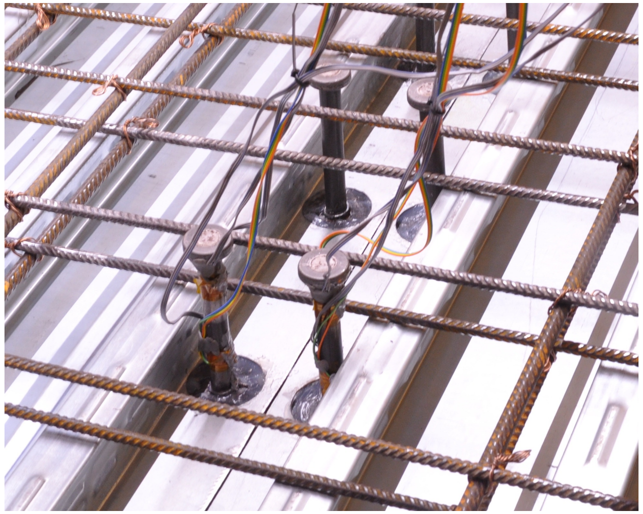


Source: El Jisr and Lignos (2025)

Instrumentation

- Digital image correlation system (8 cameras) to track strains on the slab surface
- LED Wireless tracking system for displacements
- Conventional instrumentation: About 380 other sensors

Pressure & strain gauges to deduce shear connector demands

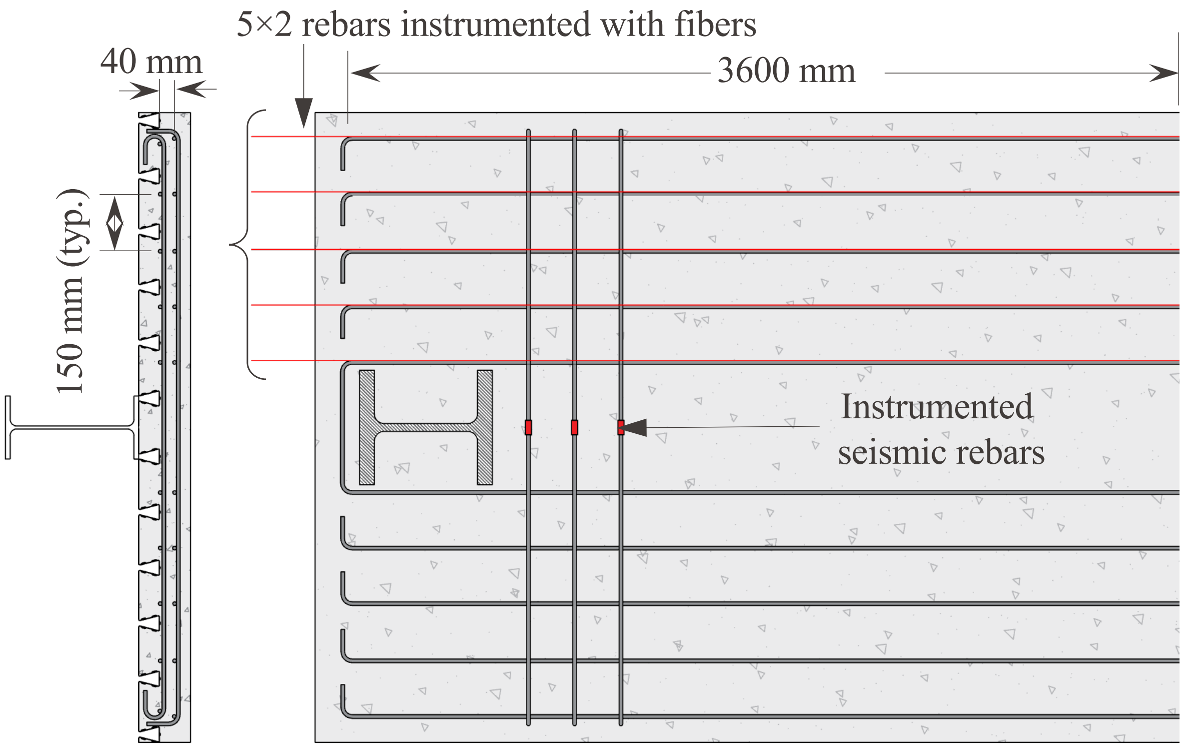


Digital image correlation system

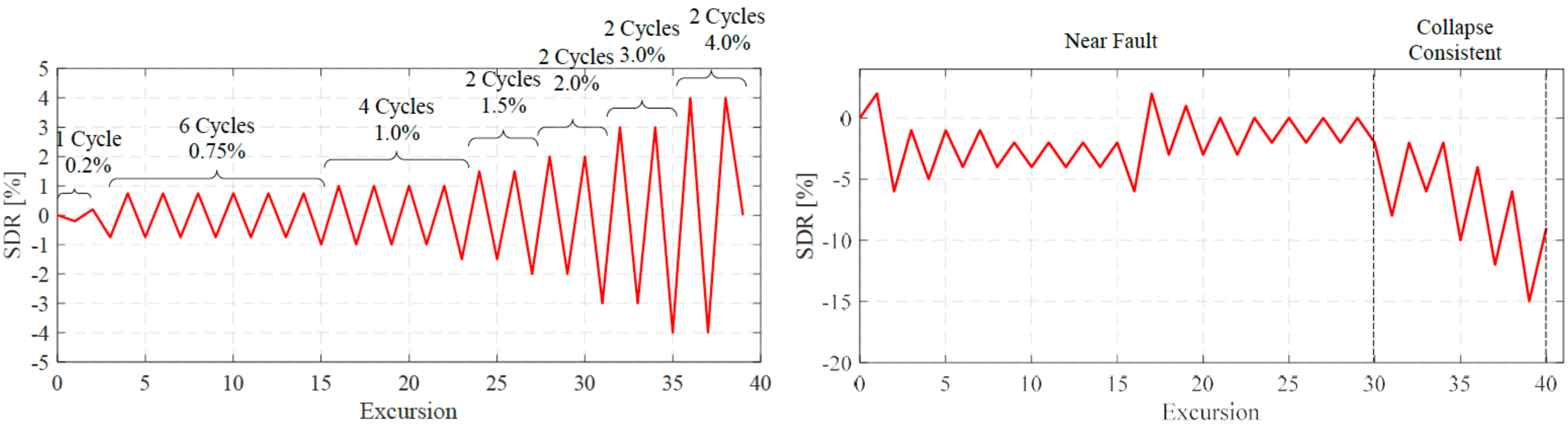
Images courtesy of D. Lignos

Instrumentation (2)

- LUNA: fiber optic cables for continuous strain measurements on steel reinforcement



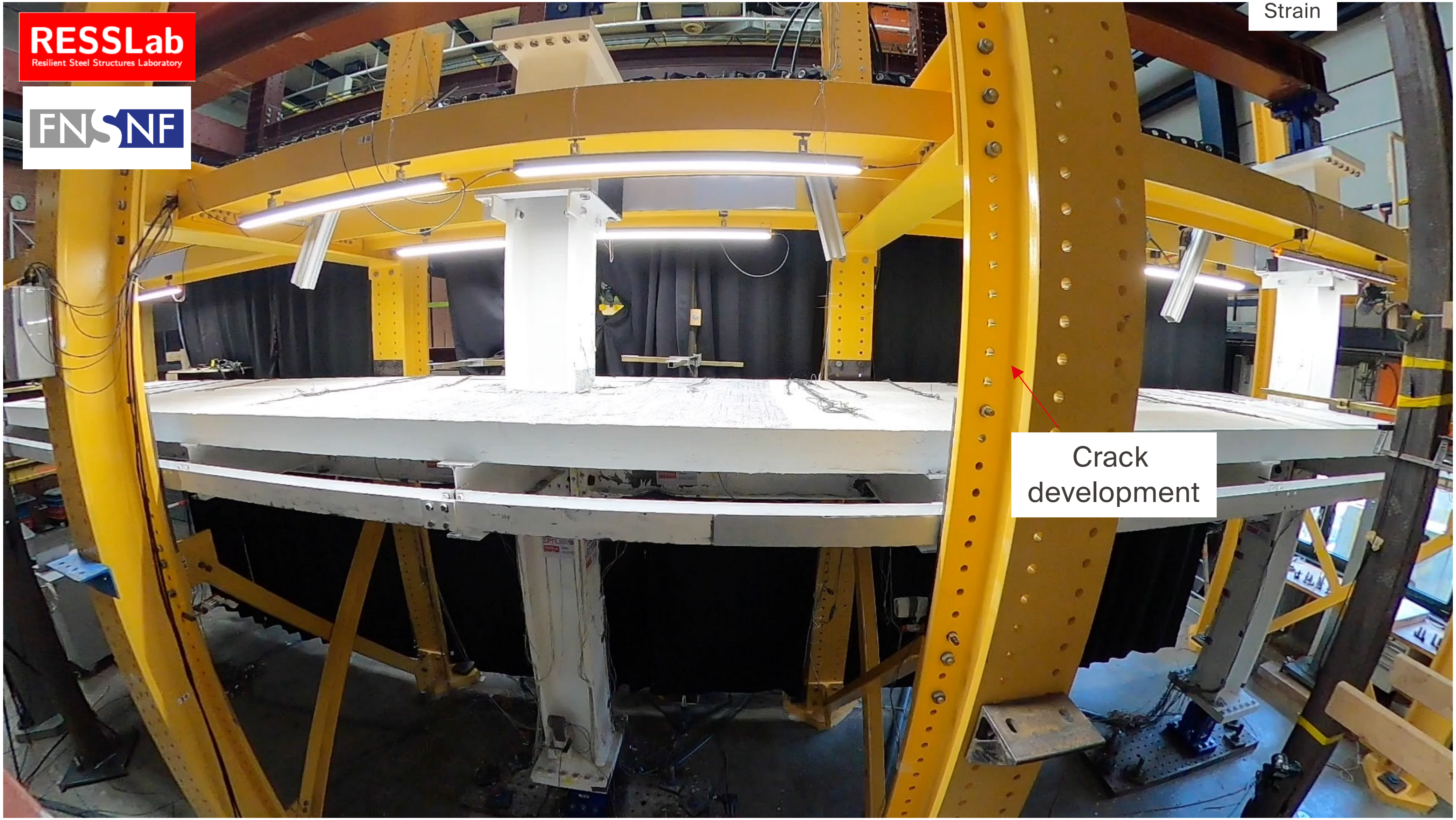
EPFL Loading protocols



- Symmetric cyclic protocol (pre-qualification of connections, CEN/TS 1998-1-101)
- SAC near fault protocol (prototype design location near fault)
- Collapse-consistent protocol to mimic “ratcheting” prior to structural collapse

Source: El Jisr and Lignos (2025)

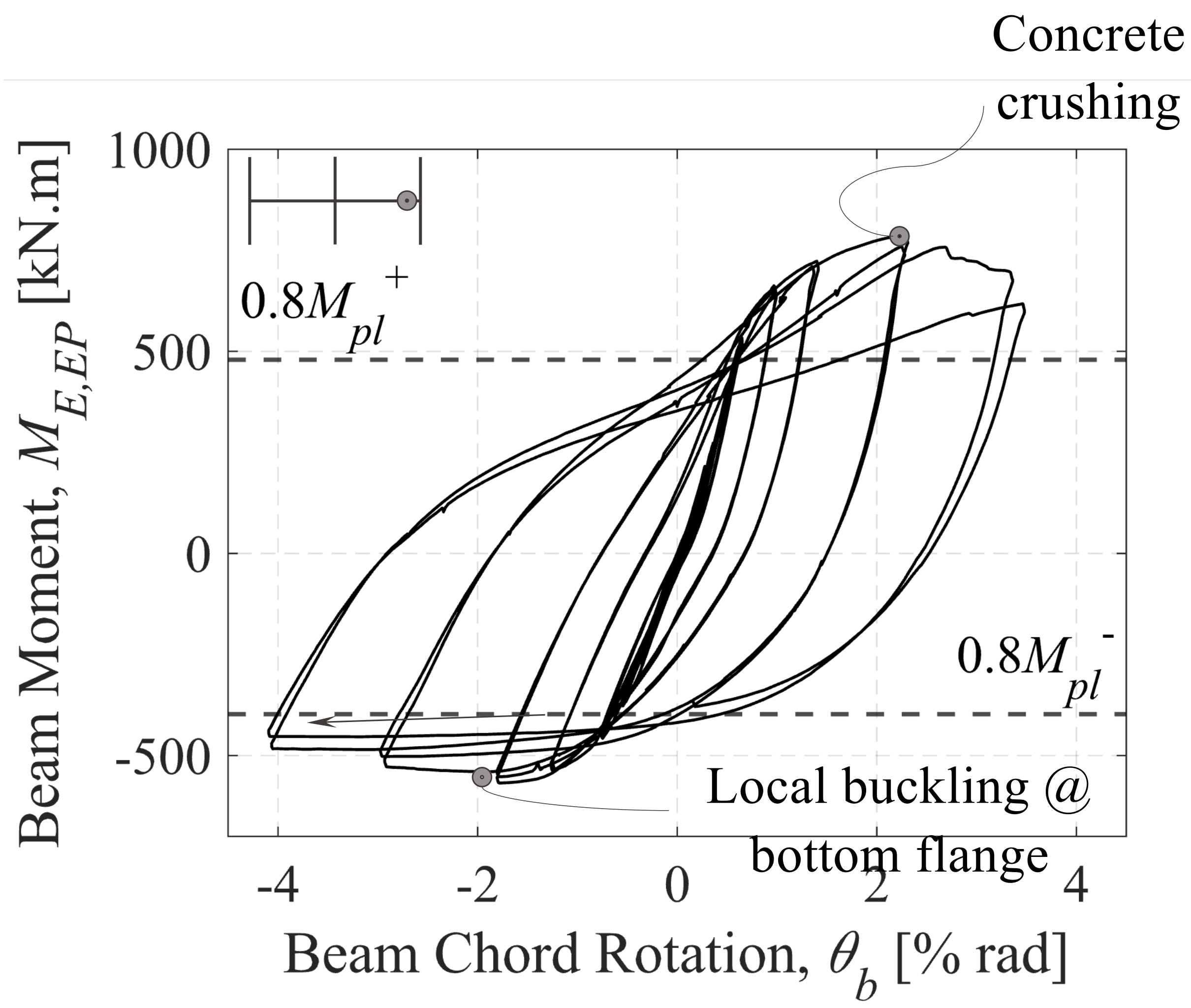
Demo: Role of the floor system at large deformations

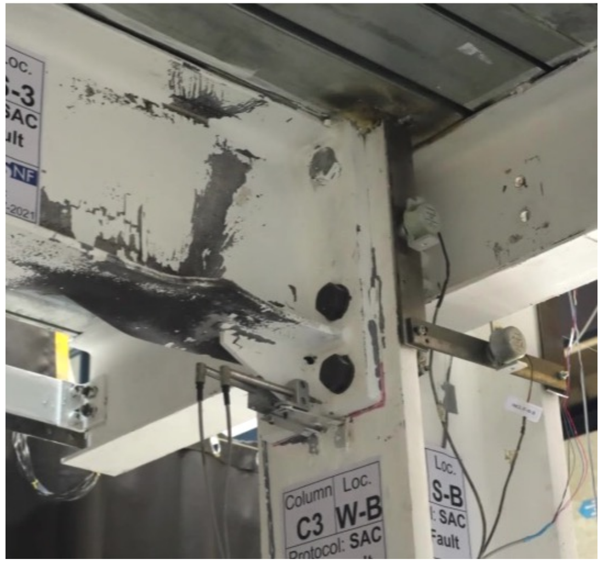


- Prof. Dimitrios G. Lignos, EPFL – Full-scale testing of a 2-bay composite steel MRF under cyclic loading

Behaviour of composite-steel beams

-Symmetric cyclic loading protocol

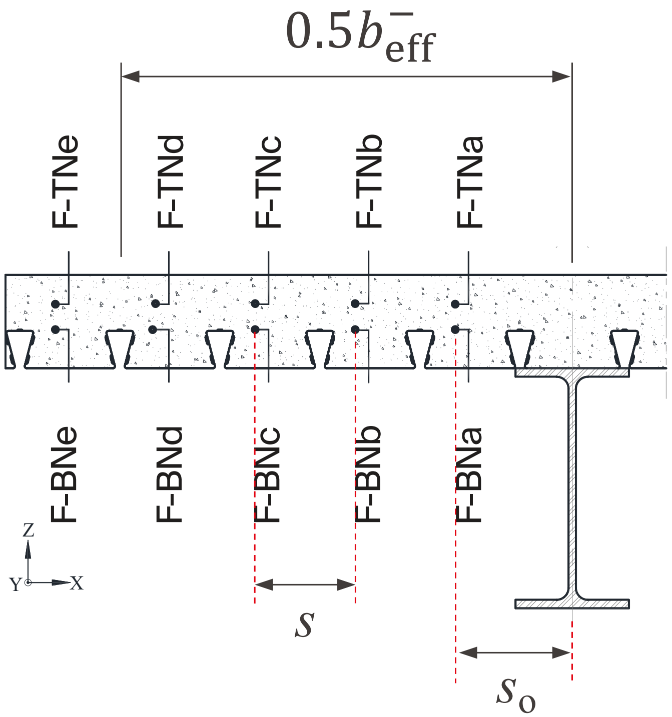


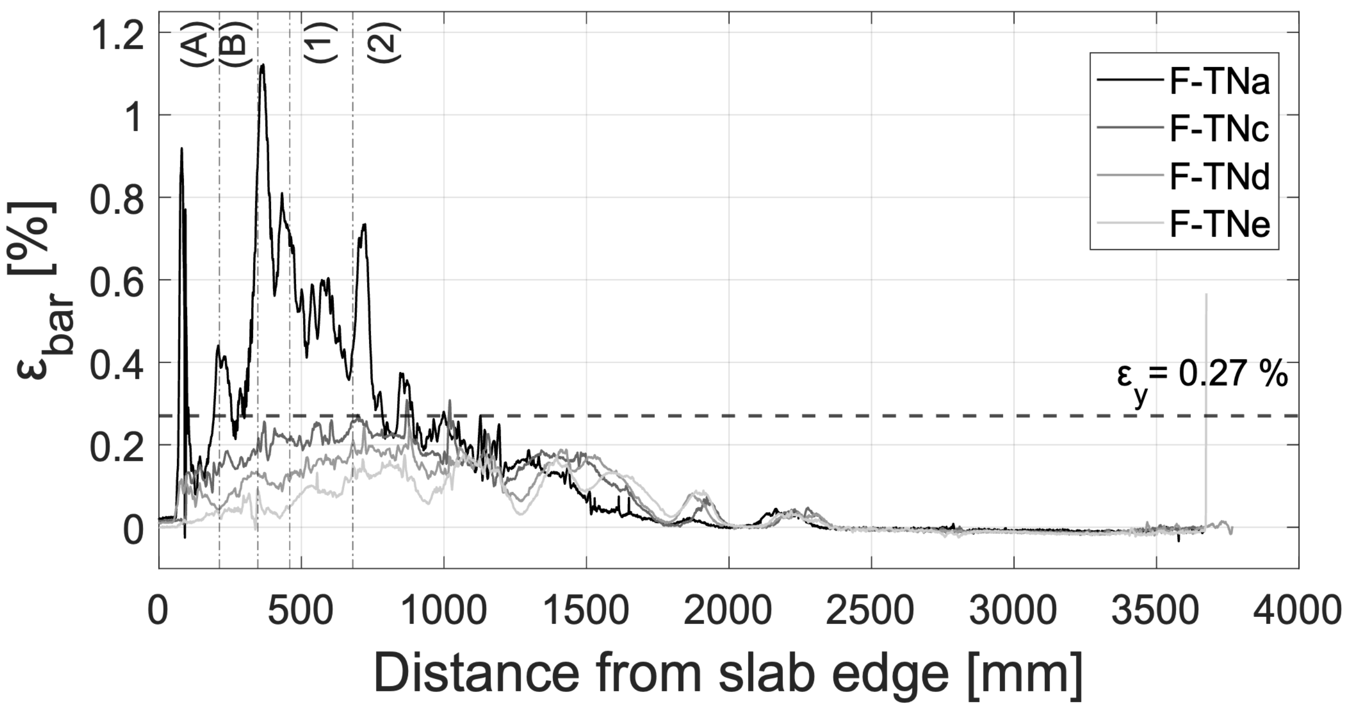


(El Jisr and Lignos, 2025)

Longitudinal strain measurements (Fiber optic cables)

-Symmetric cyclic loading protocol @ 4% rad



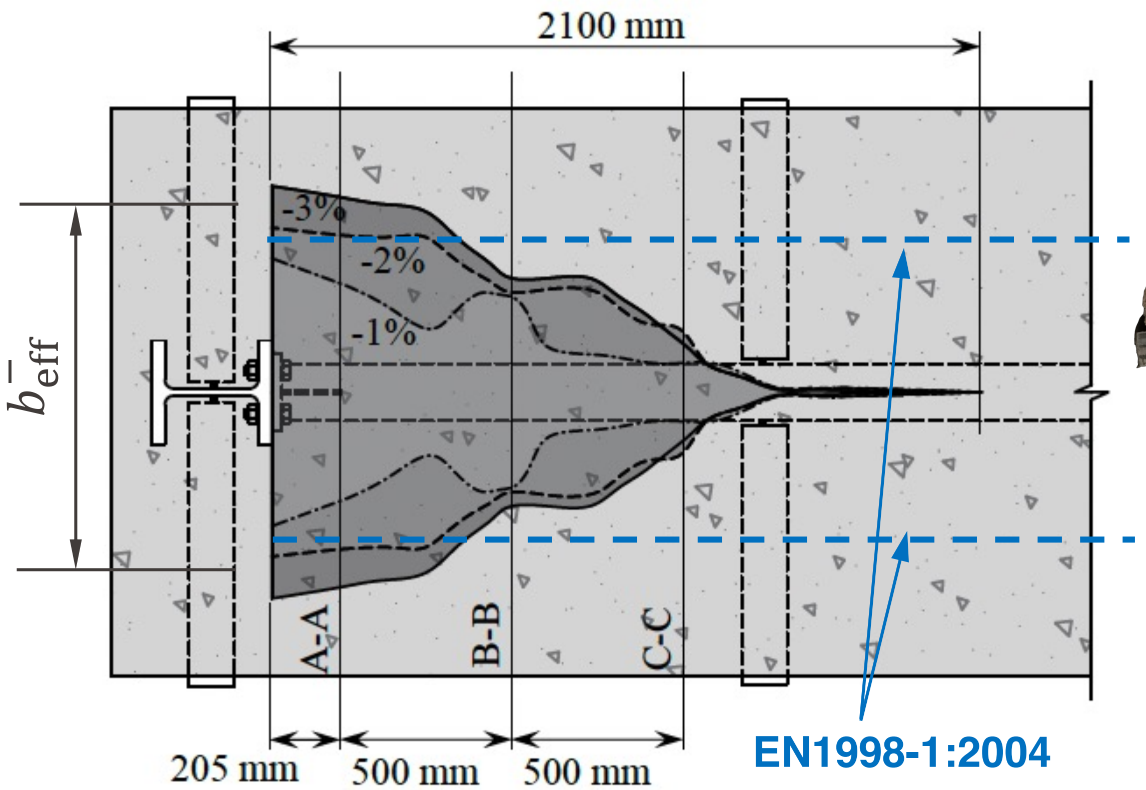


$$b_{\mathrm{eff}}^{-} = 2\left[\left(\frac{\sum \sigma_{\mathrm{s,i}}}{2 f_{\mathrm{y,n}}} - 1\right) \cdot s + s_0\right]$$

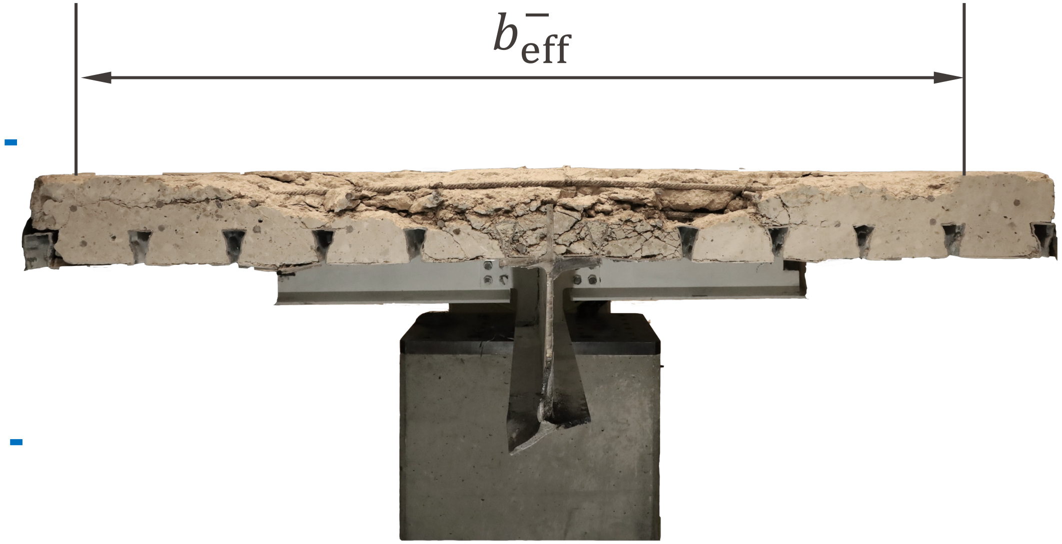
(El Jisr and Lignos, 2025)

Selected experimental findings

-Effective width evolution during cyclic loading (slab in tension)



Section cut (diamond saw): end of experiment



(El Jisr and Lignos, 2021)

Implications for EN1998-1-2: 2025

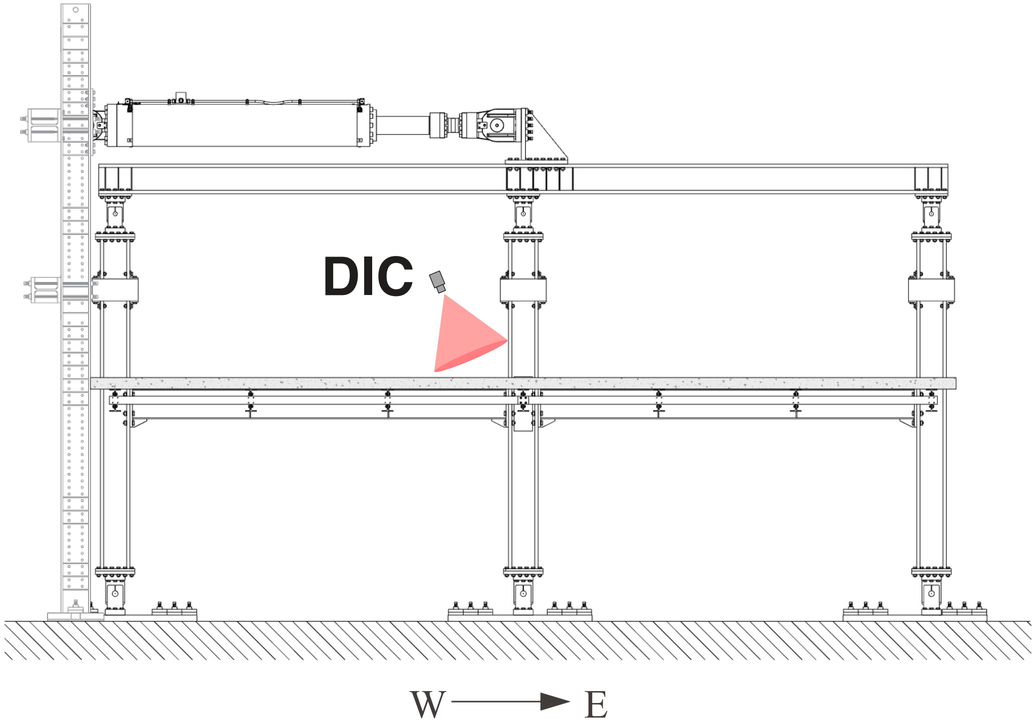
Section 12.8.6: Slab effective width for plastic bending resistance calculations

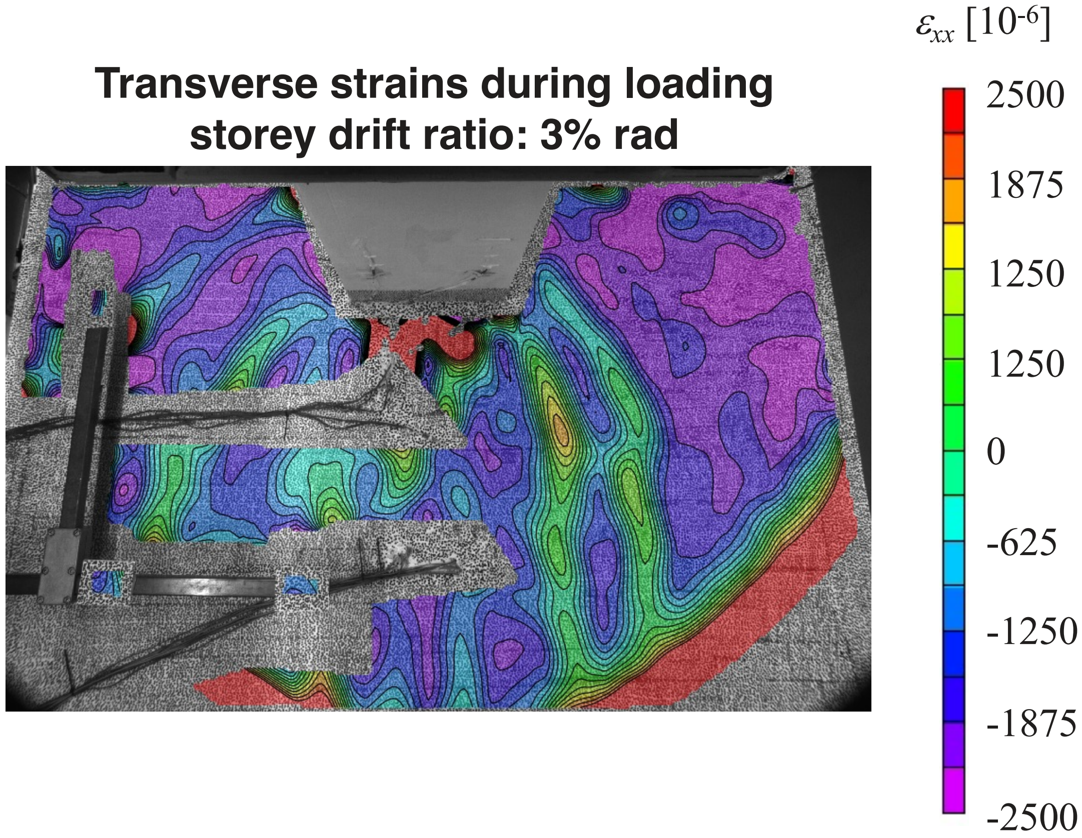
- Partial effective width $b_{\mathrm{eff,Rd}}$ of slab for evaluation of M_{Rd}

Table 12.7 (EN1998-1-2: 2025)

Stresses in slab	Column location	Transverse element	$b_{\mathrm{eff,Rd}}$
Tensile	Interior	With seismic re-bars	b_{eff}
Tensile	Exterior	With re-bars anchored to façade beam or to concrete cantilever edge strip. With seismic rebars	b_{eff}
Tensile	Exterior	With re-bars not anchored to façade beam or to concrete cantilever edge strip. With seismic rebars	0,0
Compressive	Interior/Exterior	Transverse beam with connectors and rigidly connected to column. With seismic re-bars	b_{eff}
Compressive	Interior/Exterior	No transverse beam with connectors. With seismic re-bars	$b_c+0,7h_c$
Compressive	Exterior (perimeter frame)	No transverse beam with connectors. With seismic re-bars	b_c

Insights on composite action (Digital Image Correlation)
-Effect of transverse steel beams



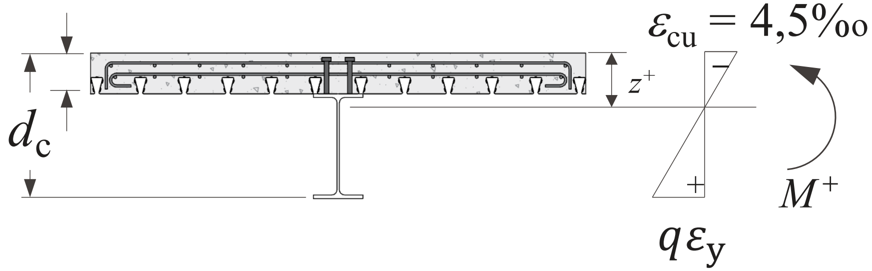


- Compressive transverse strains due to the presence of transverse beams
- Additional source of (appreciable) overstrength neglected in capacity design

(El Jisr and Lignos, 2025)

Ductility requirements for composite steel beams

-EN1998-1-2: 2025: Section 12.8.6



$$\frac{z^+}{d_c} \leq \frac{\varepsilon_{cu}}{\varepsilon_{cu} + q \cdot \varepsilon_y}$$

Section 12.8.6 in EN1998-1-2: 2025

Ductility class	***q***	***f*$_y$ (N/mm²)**	**z^+/d_c upper limit**
DC2	$1{,}5 < q \leq 3{,}5$	355	0,45
		275	0,50
		235	0,55
DC3	$3{,}5 < q \leq 5{,}0$	355	0,35
		275	0,40
		235	0,45
	$q > 5{,}0$	355	0,30
		275	0,35
		235	0,40

ε_{cu} (considers confinement effects)

Ductility requirements for composite steel beams

-Comparisons between EN1998-1-2: 2025 and EN 1998-1-1:2004

EN1998-1:2004

Fully Composite Beam										
	L [mm]	z/d								Limit
q		IPE270	IPE300	IPE330	IPE360	IPE400	IPE450	IPE500	IPE550	
1.5	5000	0.336	0.317	0.315	0.345	0.387	0.414	0.439	0.457	0.50
	6000	0.332	0.313	0.297	0.284	0.332	0.368	0.400	0.424	0.50
	7000	0.327	0.309	0.294	0.281	0.277	0.323	0.361	0.391	0.50
	8000	0.322	0.305	0.290	0.278	0.262	0.277	0.322	0.358	0.50
	9000	0.318	0.301	0.287	0.275	0.259	0.242	0.284	0.325	0.50
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EN1998-1-2:2025

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	6000	0.334	0.315	0.299	0.311	0.358	0.390	0.418	0.440	0.64
	7000	0.330	0.312	0.296	0.283	0.312	0.352	0.386	0.412	0.64
	8000	0.326	0.308	0.293	0.280	0.266	0.313	0.354	0.385	0.64
	9000	0.322	0.305	0.290	0.278	0.262	0.275	0.321	0.357	0.64
2	5000	0.338	0.318	0.337	0.364	0.403	0.428	0.451	0.467	0.57
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	7000	0.330	0.312	0.296	0.283	0.312	0.352	0.386	0.412	0.57
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	8000	0.326	0.308	0.293	0.280	0.266	0.313	0.354	0.385	0.43
	9000	0.322	0.305	0.290	0.278	0.262	0.275	0.321	0.357	0.43
5.5	5000	0.338	0.318	0.337	0.364	0.403	0.428	0.451	0.467	0.33
	6000	0.334	0.315	0.299	0.311	0.358	0.390	0.418	0.440	0.33
	7000	0.330	0.312	0.296	0.283	0.312	0.352	0.386	0.412	0.33
	8000	0.326	0.308	0.293	0.280	0.266	0.313	0.354	0.385	0.33
	9000	0.322	0.305	0.290	0.278	0.262	0.275	0.321	0.357	0.33
6.5	5000	0.338	0.318	0.337	0.364	0.403	0.428	0.451	0.467	0.29
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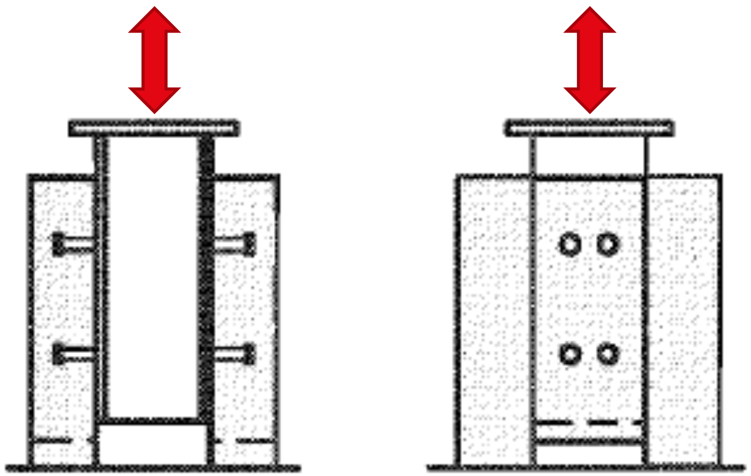
	7000	0.330	0.312	0.296	0.283	0.312	0.352	0.386	0.412	0.29
	8000	0.326	0.308	0.293	0.280	0.266	0.313	0.354	0.385	0.29
	9000	0.322	0.305	0.290	0.278	0.262	0.275	0.321	0.357	0.29

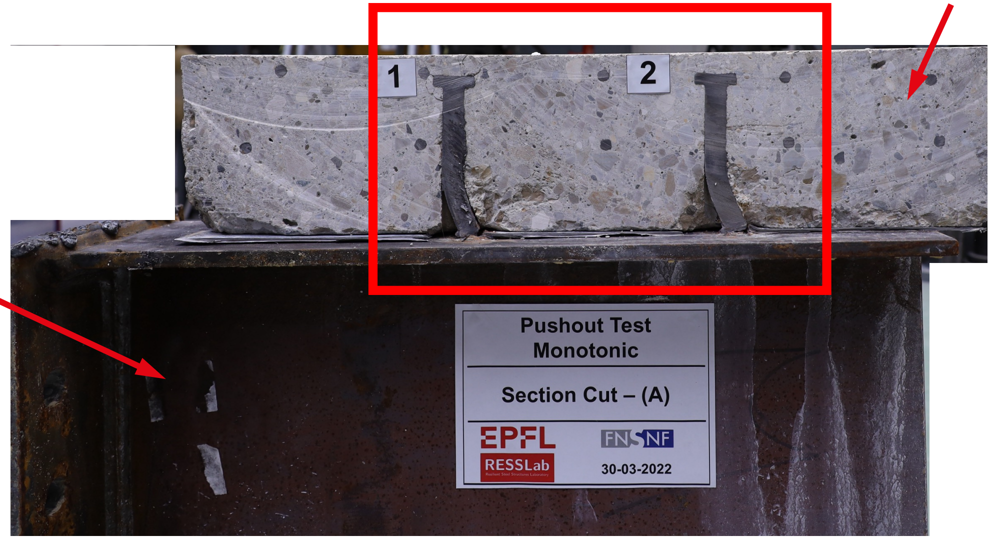
Behaviour of shear connectors

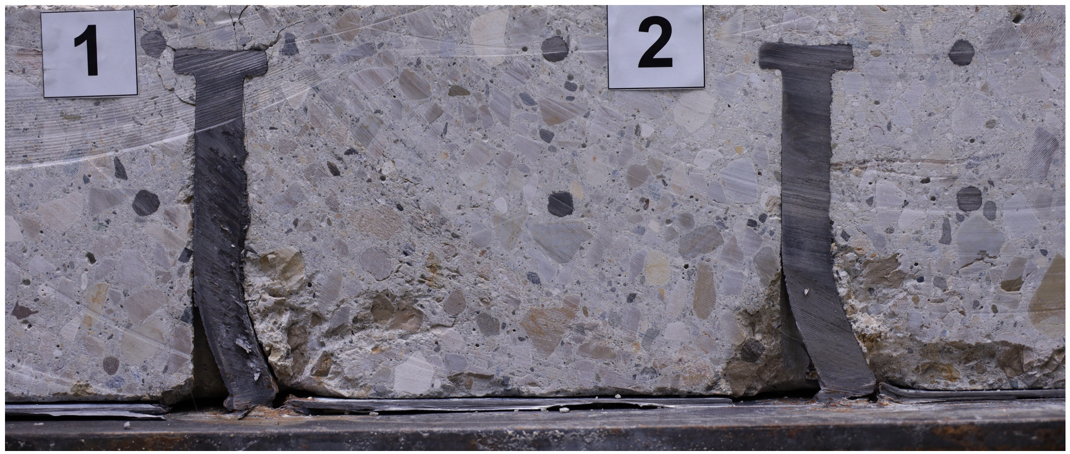
-From typical push-out test



Push-out test

Source: EN 1994-1-1 Annex D (2004)



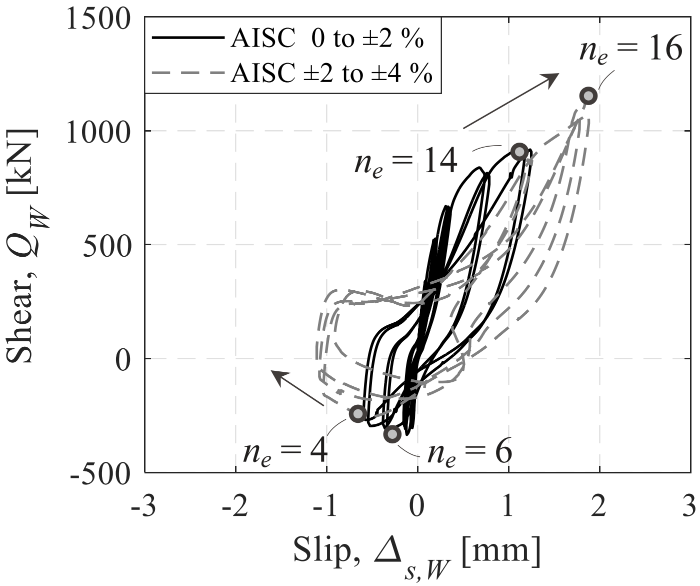


(El Jisr and Lignos, 2025)

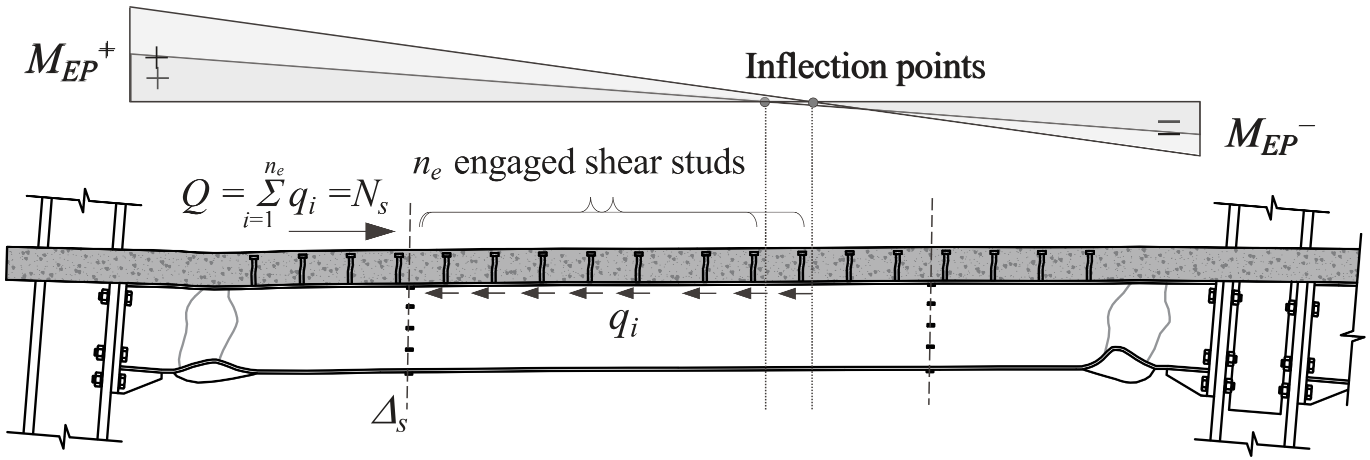
Behaviour of shear connectors

-From frame response

Beam-slab response of stud group



Shear stud participation during loading



(El Jisr and Lignos, 2025)

Behaviour of shear connectors (2)

-From frame response

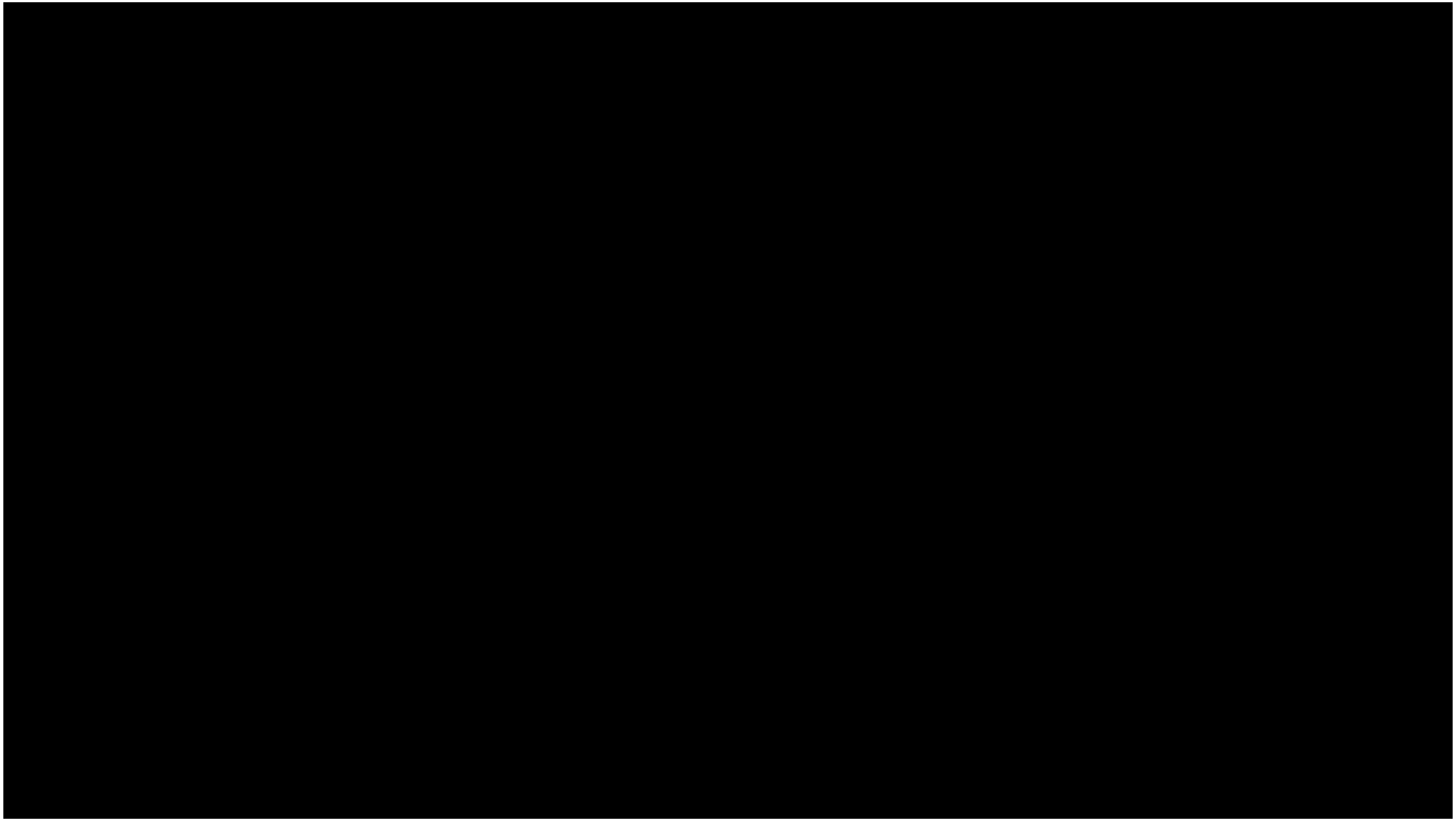
Slab

Steel beam (IPE330)

No localization effects

(El Jisr and Lignos, 2025)

Few words on columns



Elkady and Lignos (2018)

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Steel & composite-steel columns

-New design requirements in DC2 & DC3 in EN1998-1-2:2025

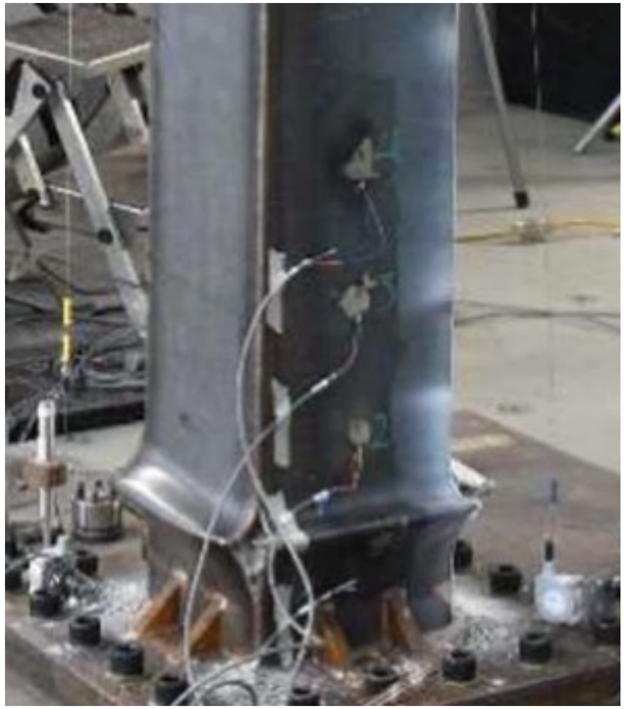
Section 11.9 (H-, I- or HSS)

$$\frac{N_{\mathrm{Ed,G}}}{N_{\mathrm{pl,Rd}}} \leq 0{,}30$$

Suzuki and Lignos (2021)

Section 12.9 (Filled composite)

$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{pl,Rd}}} \leq 0{,}75$$

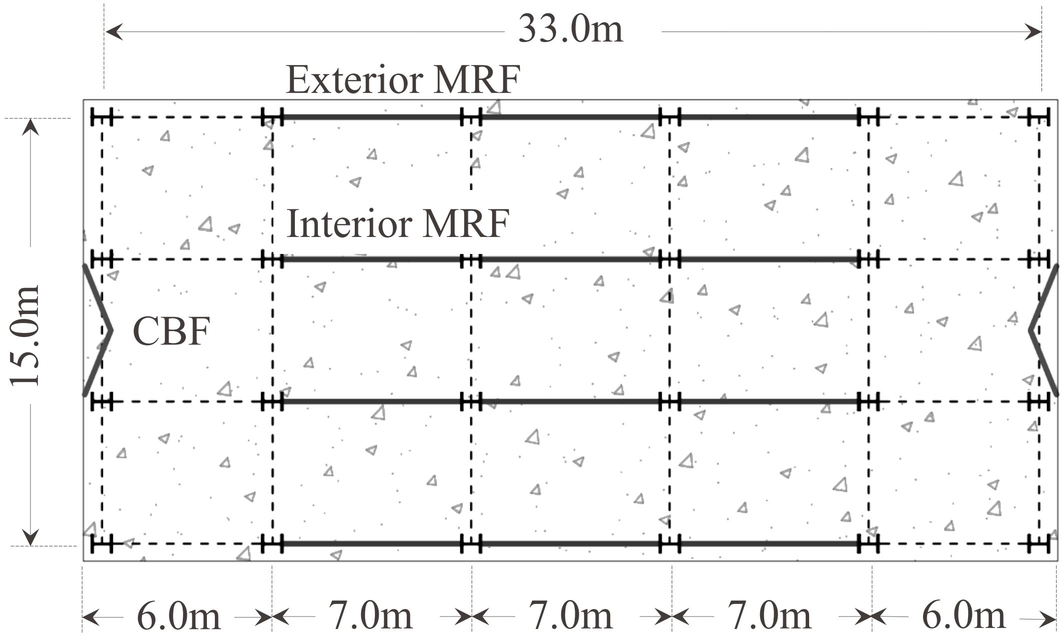


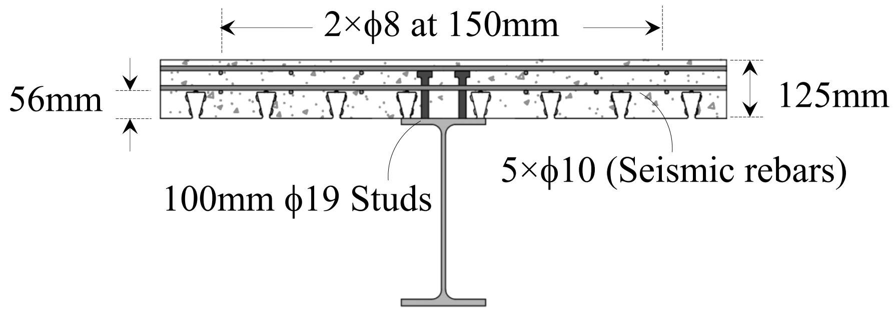
Farahi, Lignos et al. (2022)

System-level studies: Composite steel MRF Buildings

Prototype buildings according to EN1998-1-2: 2025 (Ductility Class 2)

- Design location: Sion, Katerini, Braila

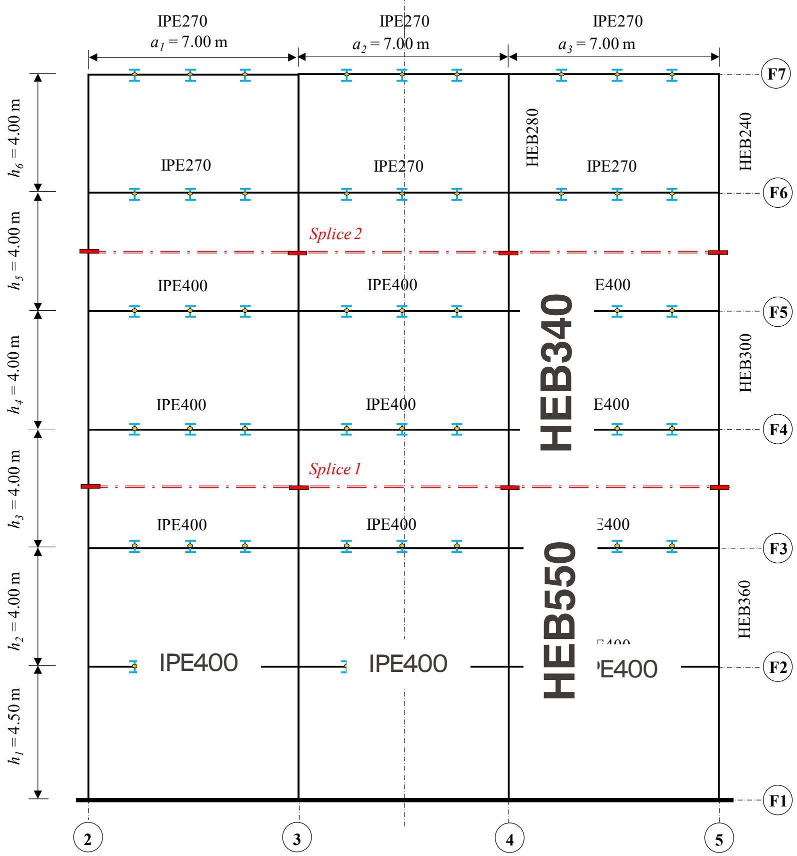




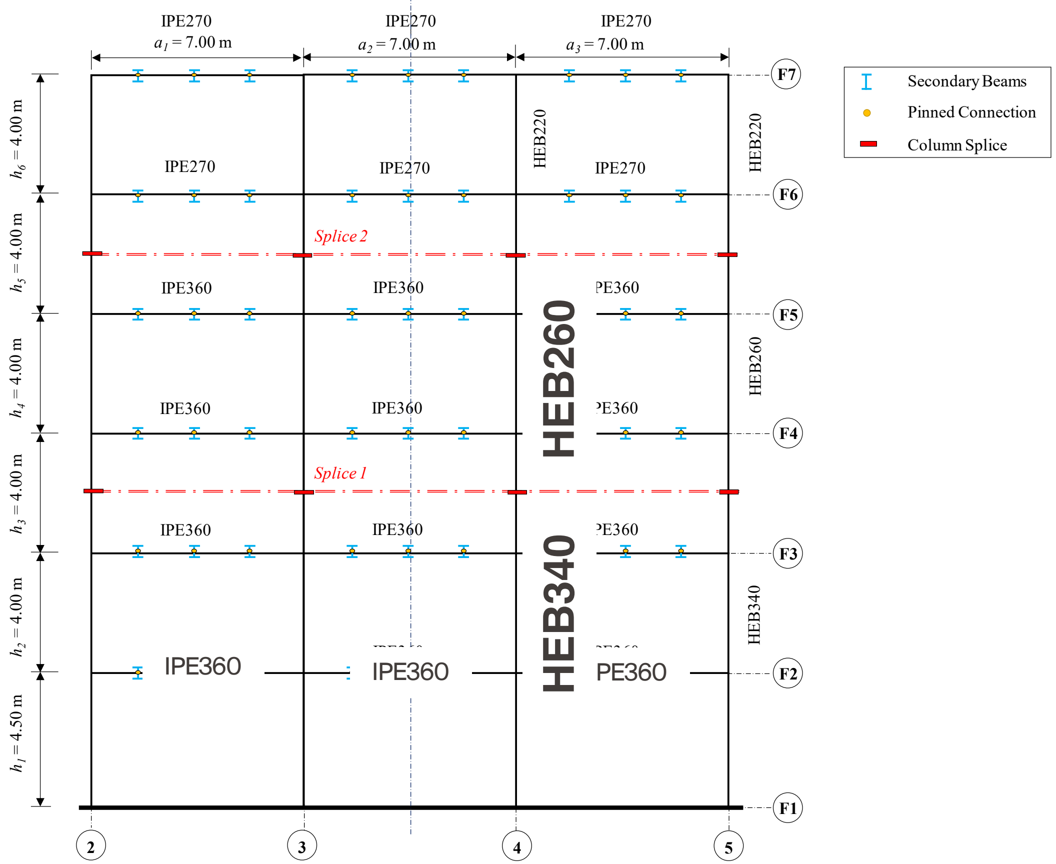
Steel weight comparisons (~20% weight reduction)

-EN1998-1-1:2004 versus EN1998-1-2:2025

EN1998-1-1:2004 (DCM)

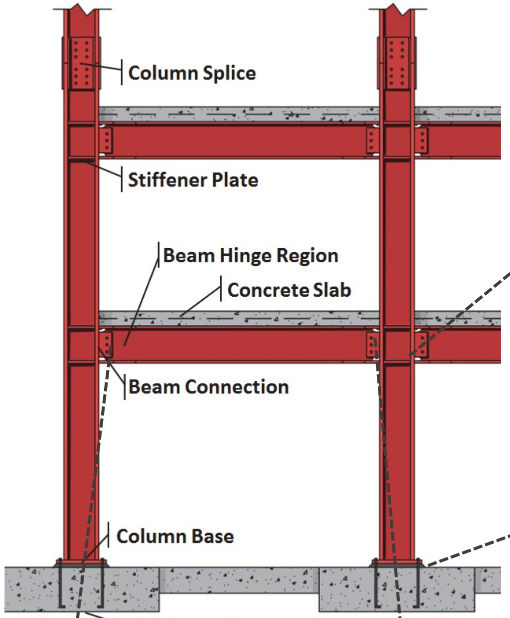


EN1998-1-2:2025 (DC2)



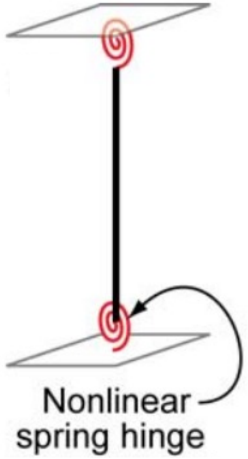
Source: El Jisr and Lignos (2020)

Model fidelity



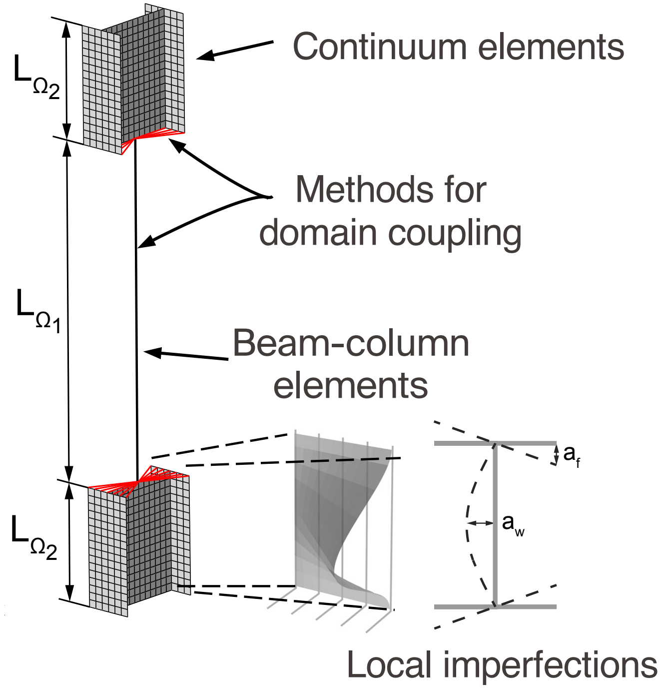
@NIST (2017)

Concentrated plasticity



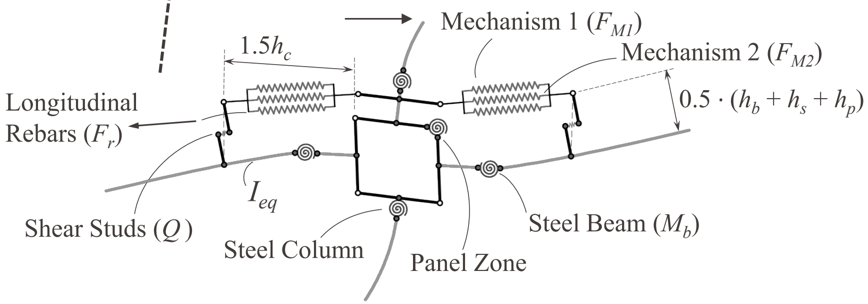
Lignos et al. (2011, 2019)

High fidelity Domain coupling



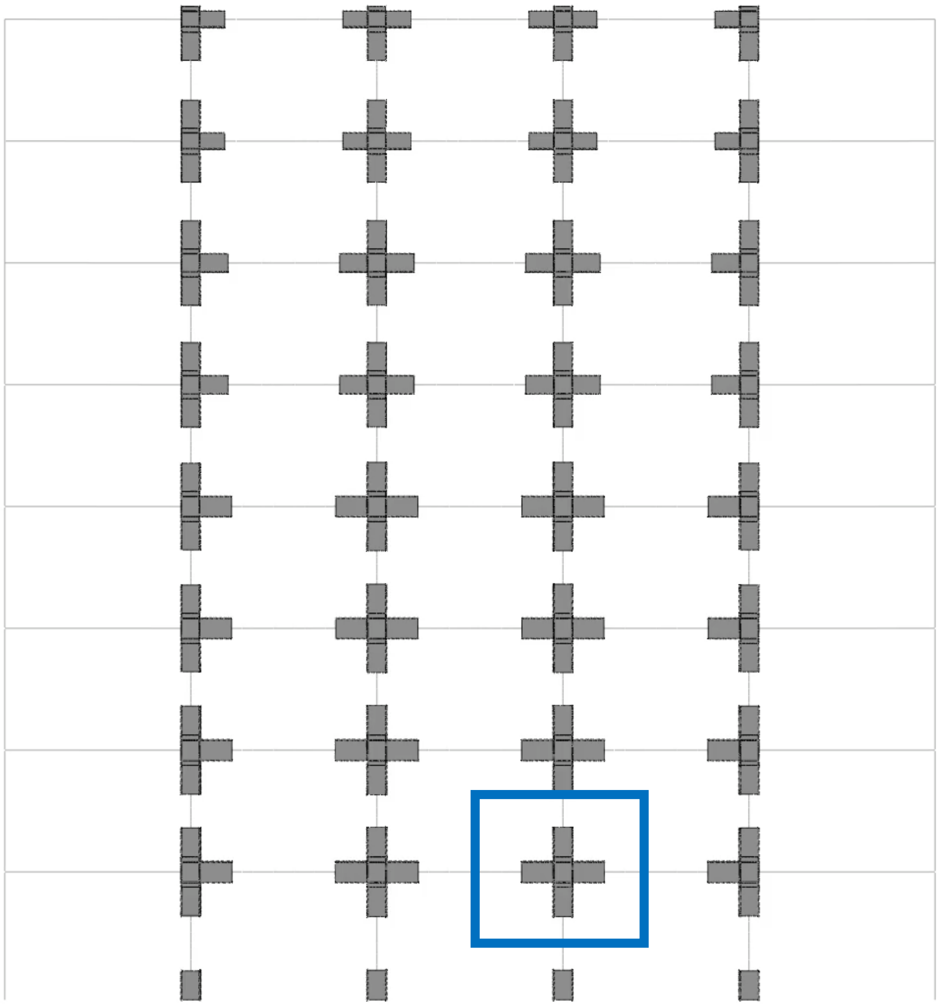
Hartloper et al. (2021, 2022, 2023)

Heredia Rosa et al. (2024, 2025a, b)

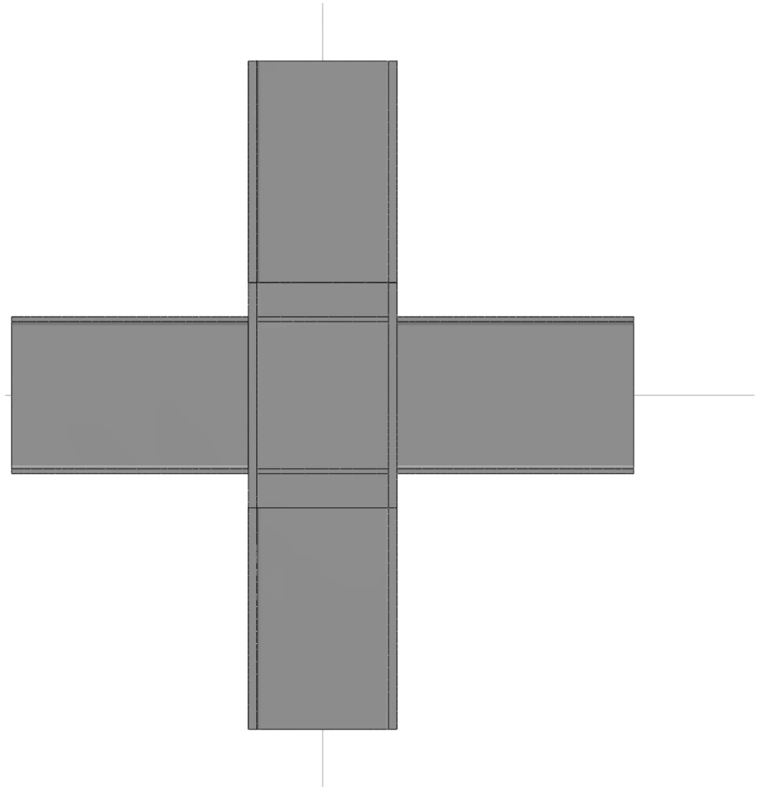


El Jisr, Kohrangi, and Lignos (2022)

High resolution modeling
-Implementation into ABAQUS (with our plug-in interface elements)

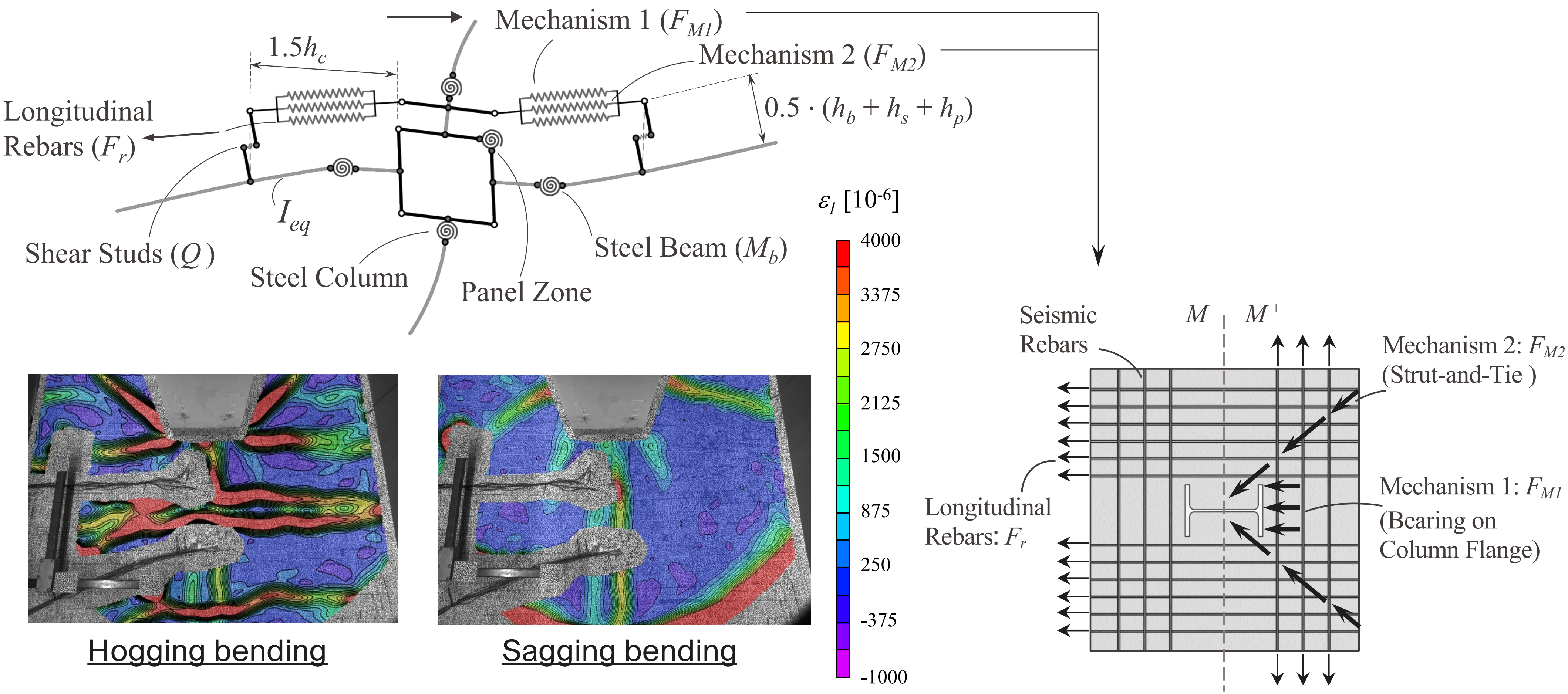


Local response



Gu, Skiadopoulos and Lignos (2026*)

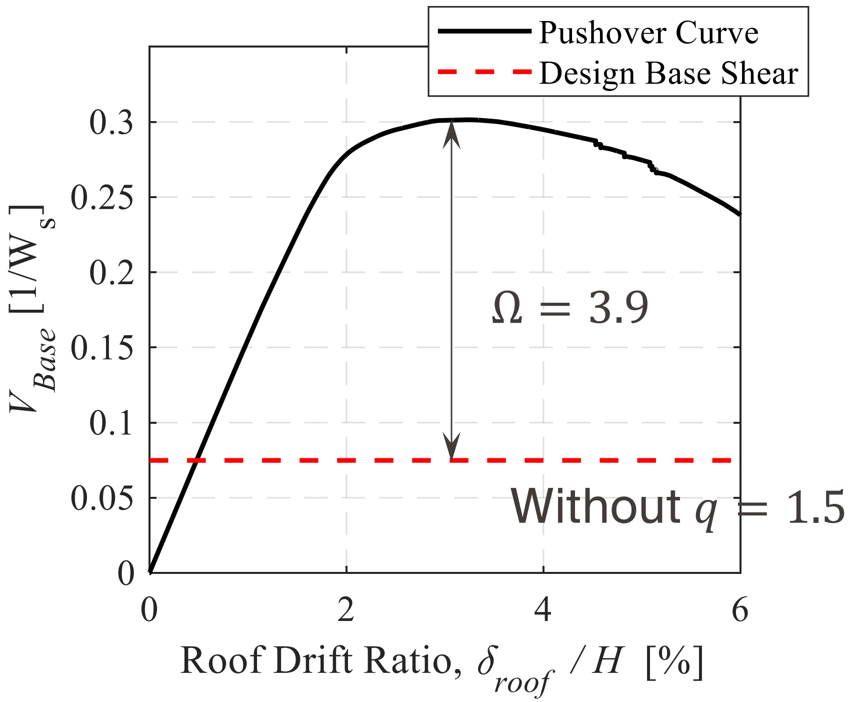
Macro model for composite steel beams
-Implementation into OpenSees simulation platform



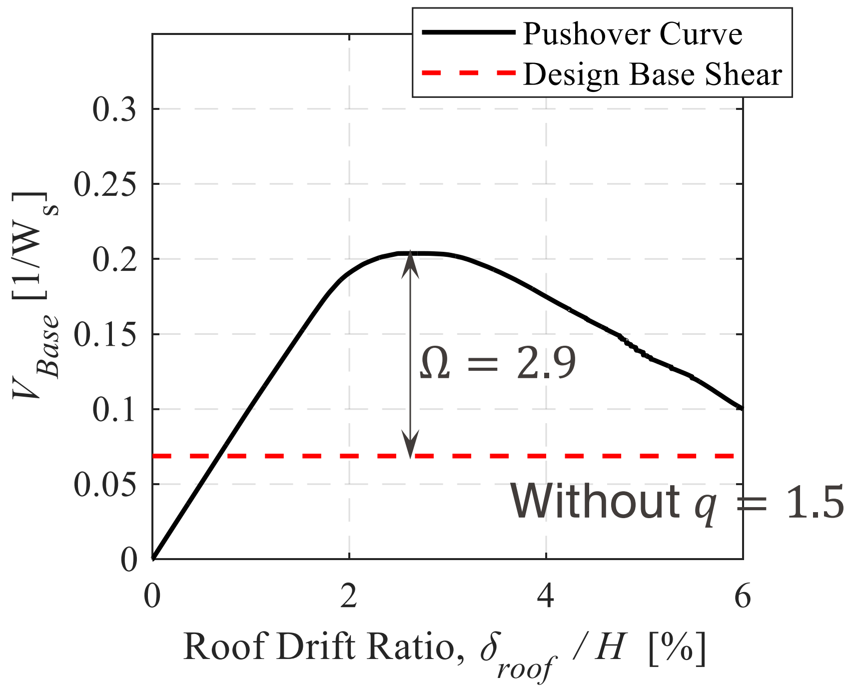
El Jisr, Kohrangi, and Lignos (2022)

Comparisons of seismic behaviour
-Pushover analysis

EN1998-1:2004 (DCM)



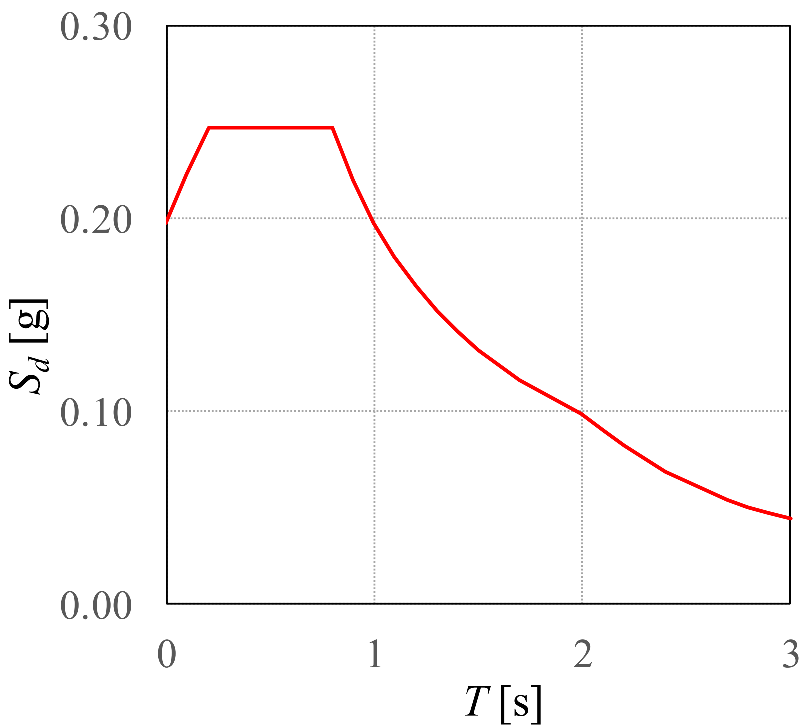
EN1998-1-2:2025 (DC2)

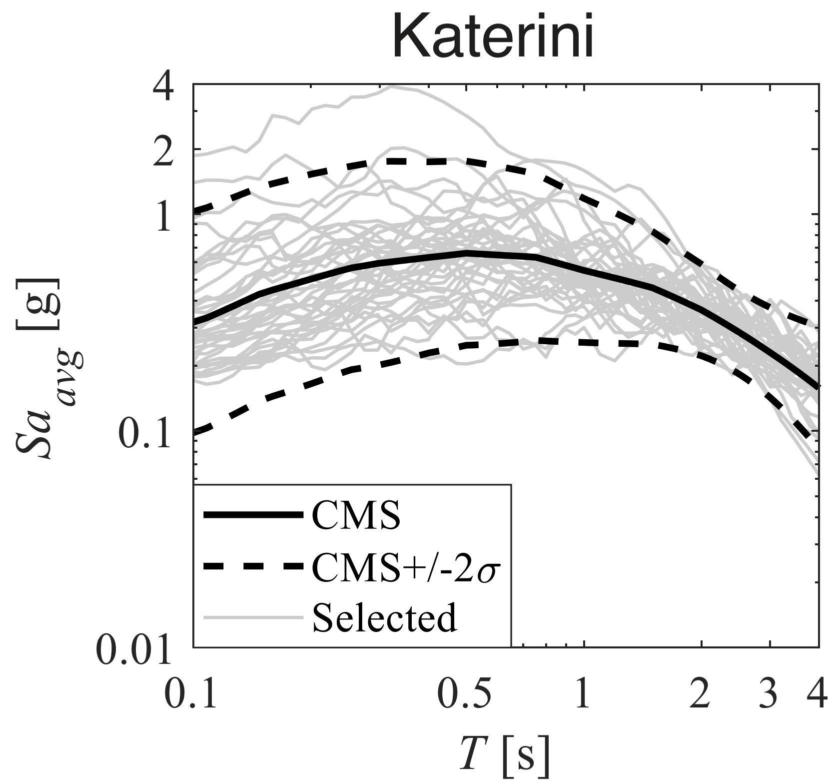


Source: El Jisr and Lignos (2025)

Nonlinear response history analyses
-Ground motion selection

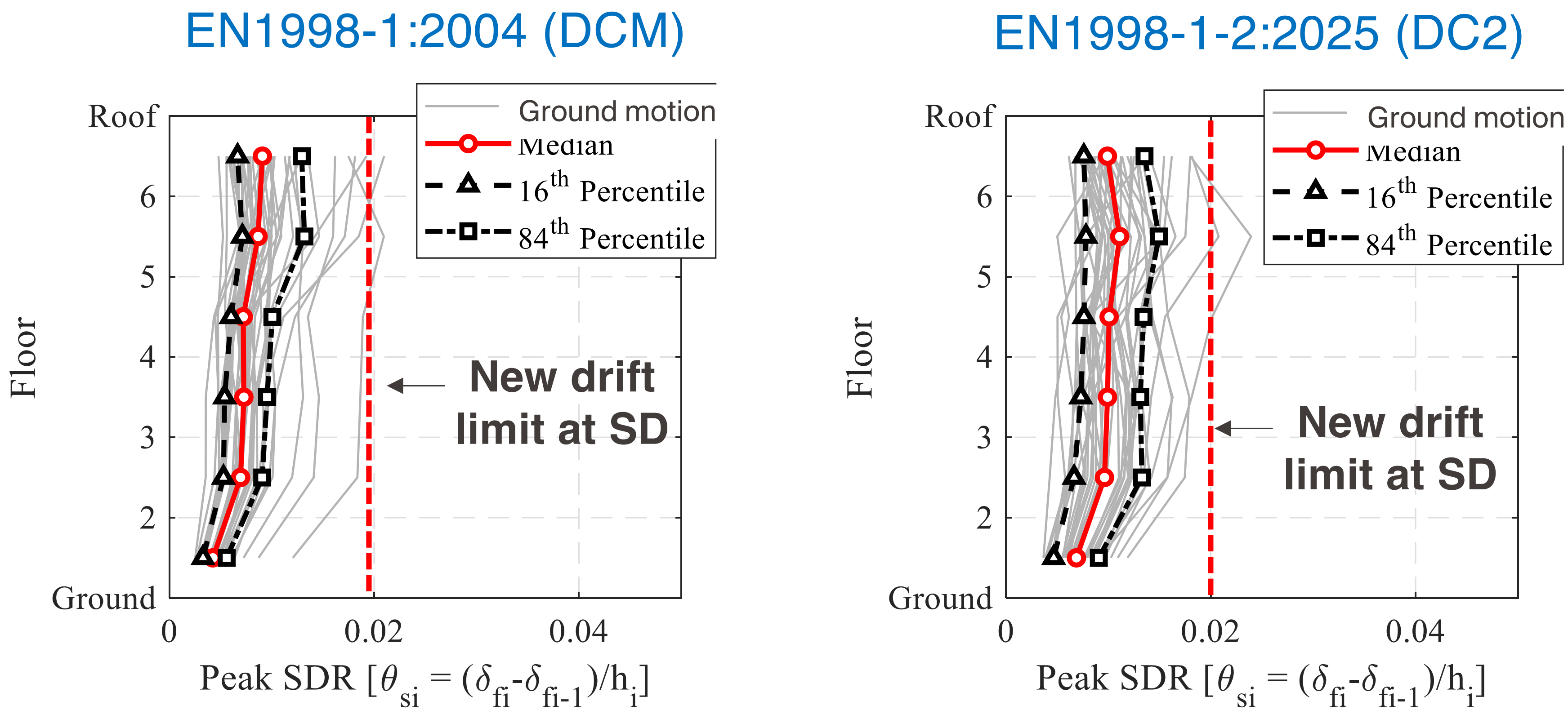
- 40 ground motions per location, T_R = 2475 years





El Jisr, Kohrangi, and Lignos (2022)

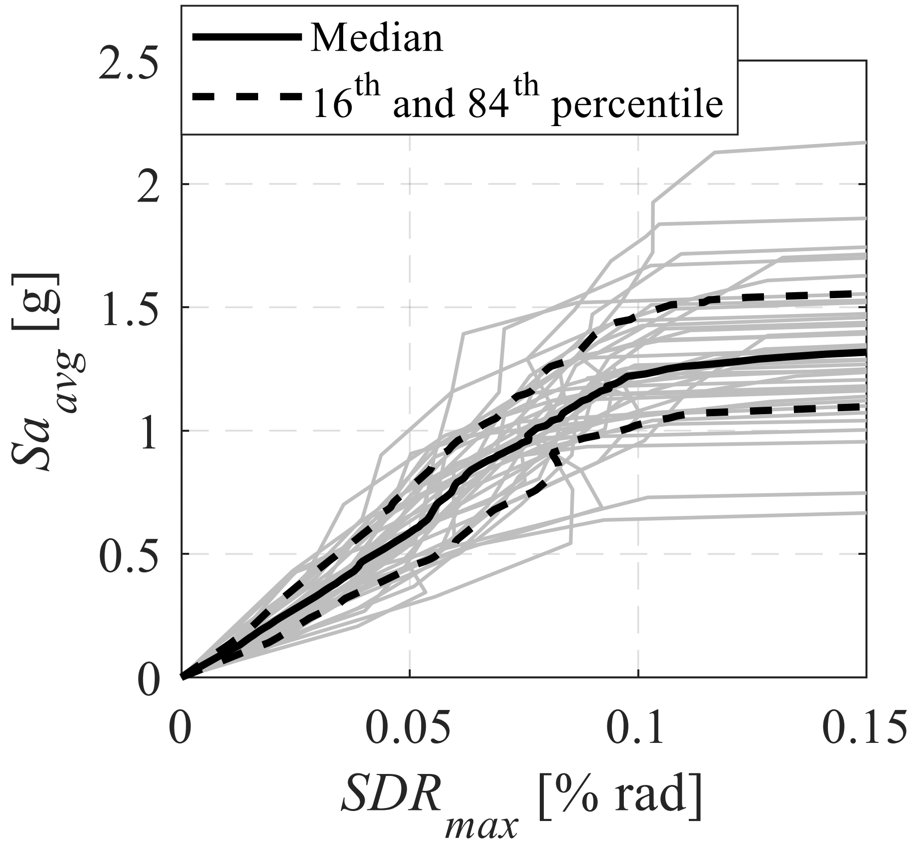
Nonlinear response history analyses
-Comparisons at significant damage (SD) limit state



Source: El Jisr and Lignos (2025)

Nonlinear response history analyses

-Collapse risk benchmarking: EN1998-1-2:2025 Ductility Class 2 (DC2)



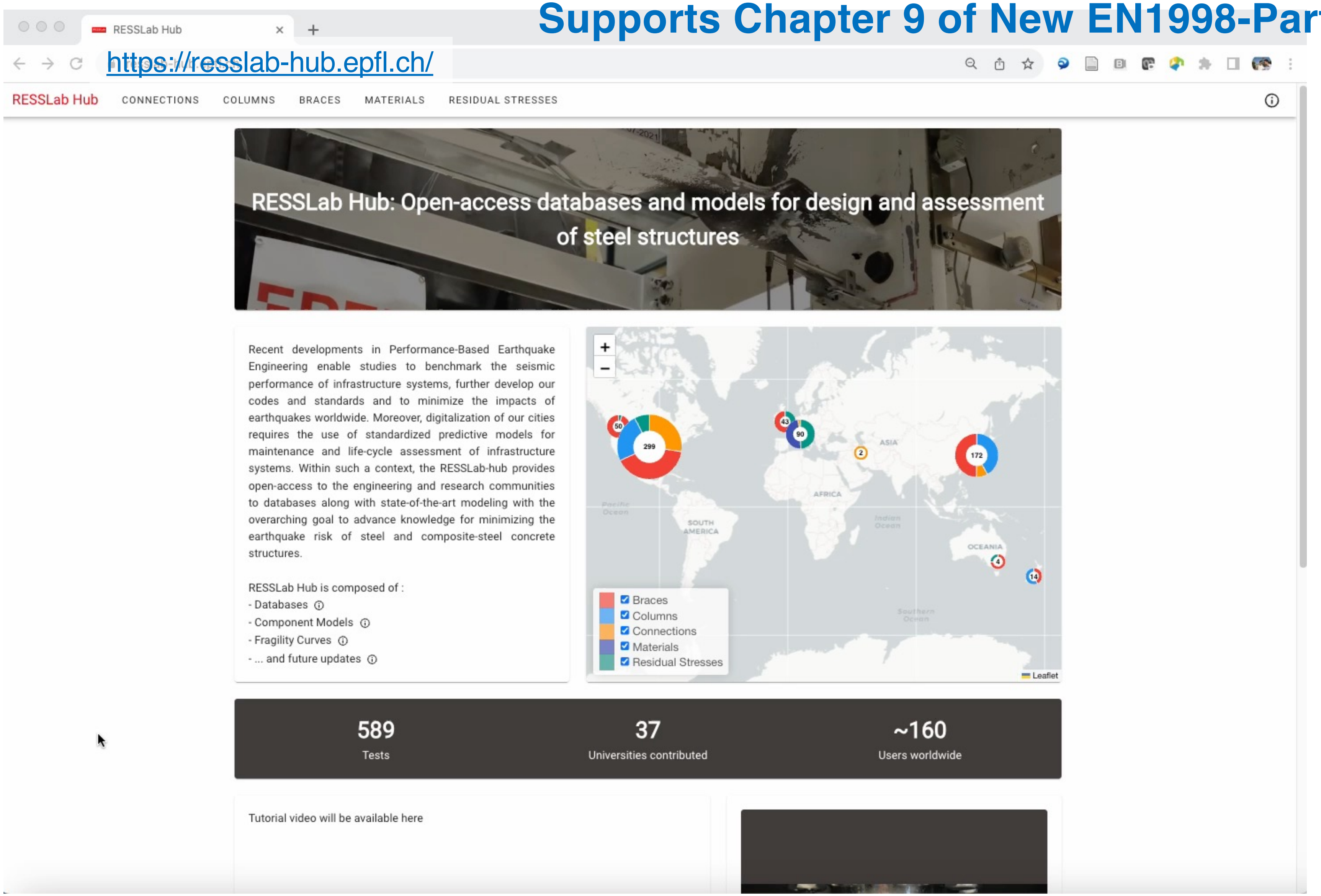
Annualized probability of collapse over 50 years
(target: 1% over 50 years life expectancy)

	Degree of Composite Action		
Site	$n = 100\%$	$n = 80\%$	$n = 50\%$
Sion	0.003%	0.004%	0.005%
Katerini	0.021%	0.025%	0.033%
Braila	0.0001%	0.0002%	0.0002%

Source: El Jisr and Lignos (2025)

Open access databases & models for assessment of steel structures

Supports Chapter 9 of New EN1998-Part 3

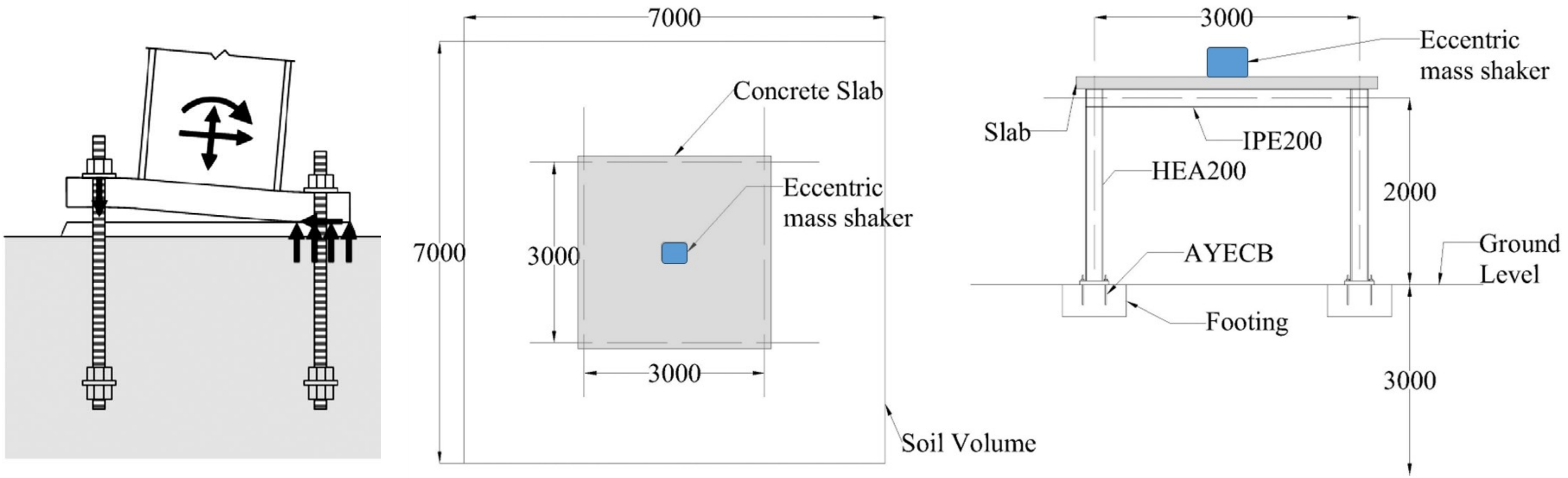


Collaborative efforts
-With Greek universities

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

ENGINEERING RESEARCH INFRASTRUCTURES FOR EUROPEAN SYNERGIES

- Prof. D. Pitilakis
- Dissipative column base connections including soil structure interaction
  - Informs Annex H of EN1998-1-2:2025



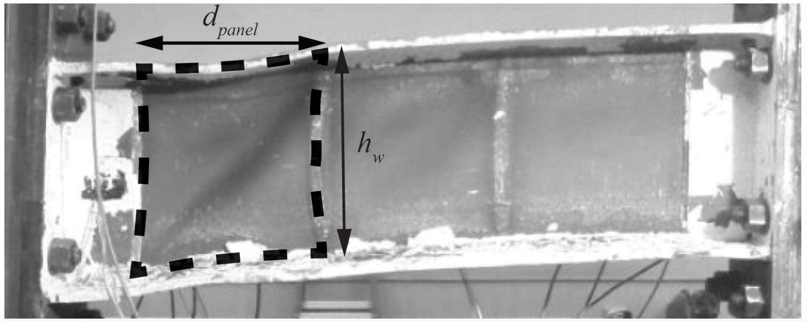
Collaborative efforts (2)

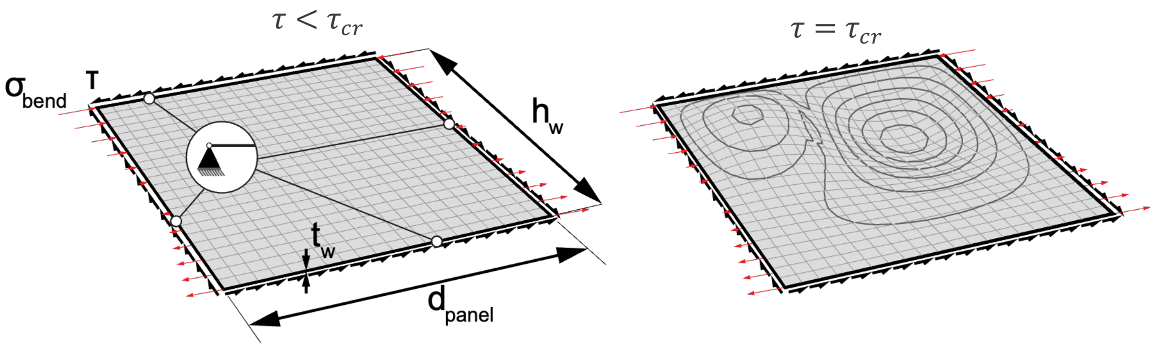
-With Greek universities

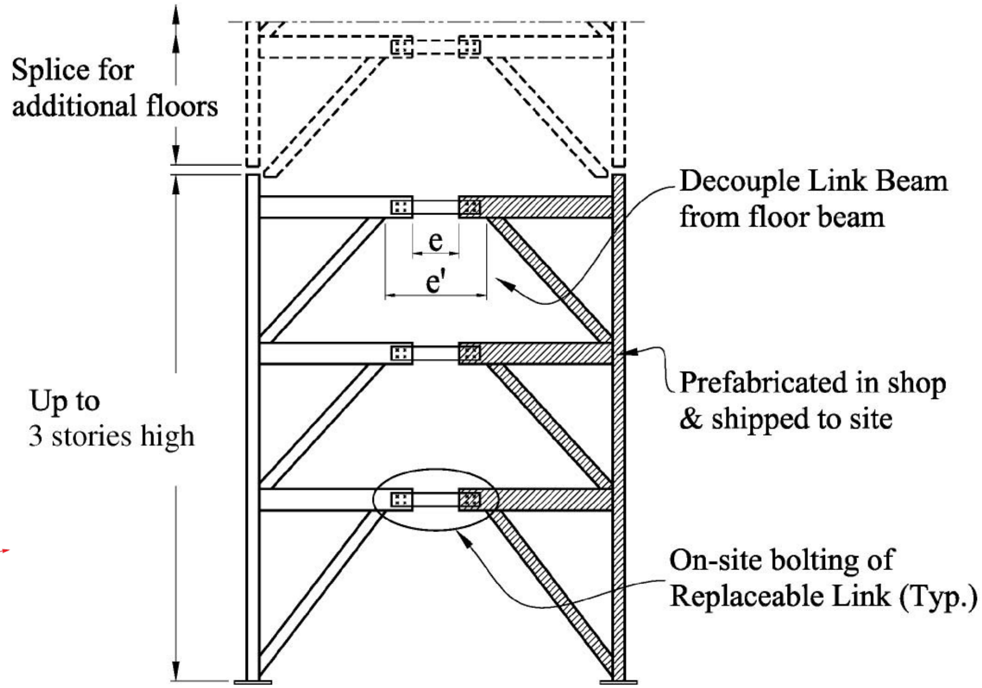
BODOSSAKI FOUNDATION

ENAC EPFL Flagship program

- ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ UNIVERSITY OF PATRAS Prof. T. L. Karavasilis (Dr. N. Skretas)
- Stiffener spacing requirements for eccentric braced frames
  - Form the basis for new provisions in EN1998-1-2:2025 and AISC-341-27







Skretas, Karavasilis and Lignos (2024, 2025)

Summary & conclusions

Key contributions in revisions of EN1998-1-2: 2025 (Chapters 11 and 12)

- **Slab effective width**
  - Benchmarking corresponds to 2% rad (SD limit state)
  - Higher drifts: 20 to 30% higher (influences beam-to-column joint designs)
- **Resistance of shear connectors (shear studs)**
  - 25% reduction: not imperative for beam depths less than 500mm
- **Ductility requirements for composite steel beams**
  - Confinement effects assist to relax current requirements
  - New requirements provide large flexibility in composite floor designs
- **Steel and composite columns**
  - New limits on axial load demands: to control axial shortening
- **System level seismic behaviour & economics (Ductility Class 2)**
  - Examined cases meet the collapse risk target (1% in 50 years)
  - Lighter designs may be anticipated on the lateral load resisting system

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Thank you for your kind attention!

Questions: dimitrios.lignos@epfl.ch