TOWARDS TEST-INFORMED MODELLING AND DESIGN OF VENTILATED FACADE SYSTEMS: AN OVERVIEW

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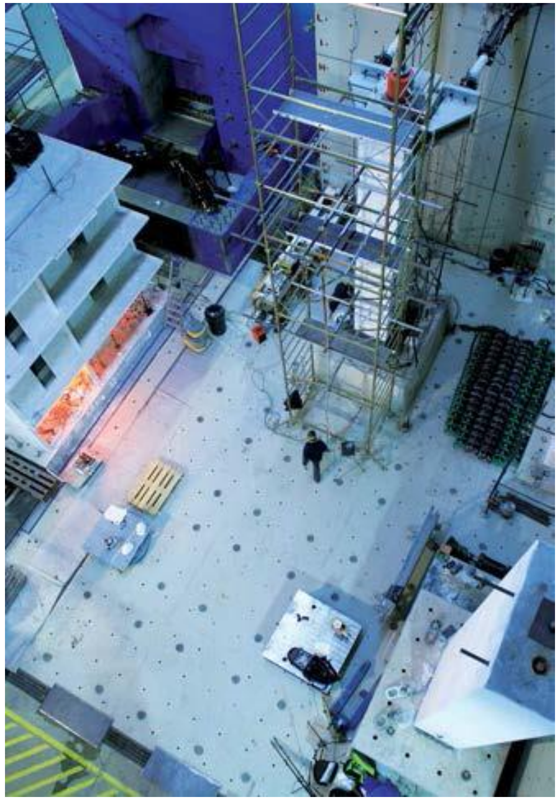
WHAT IS EUCENTRE?

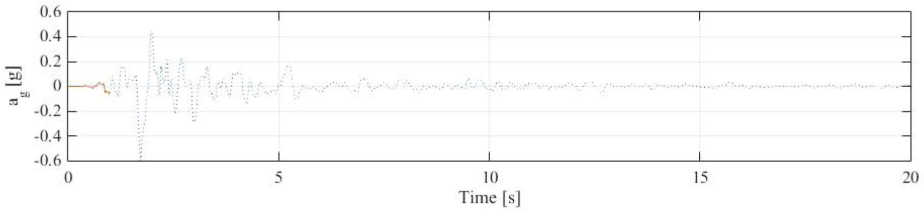
A private non-profit foundation that pursues a mission of research, training and service provision in the field of earthquake engineering and, more generally, of risk engineering

Established by four Founders, the University of Pavia, the University School for Advanced Studies IUSS of Pavia, the Italian Department of Civil Protection, the National Institute of Geophysics and Volcanology



WHAT IS EUCENTRE?

Important asset of experimental labs consisting of shaking tables able to reproduce any seismic event for testing both structural and non-structural elements and for the qualification of anti-seismic devices



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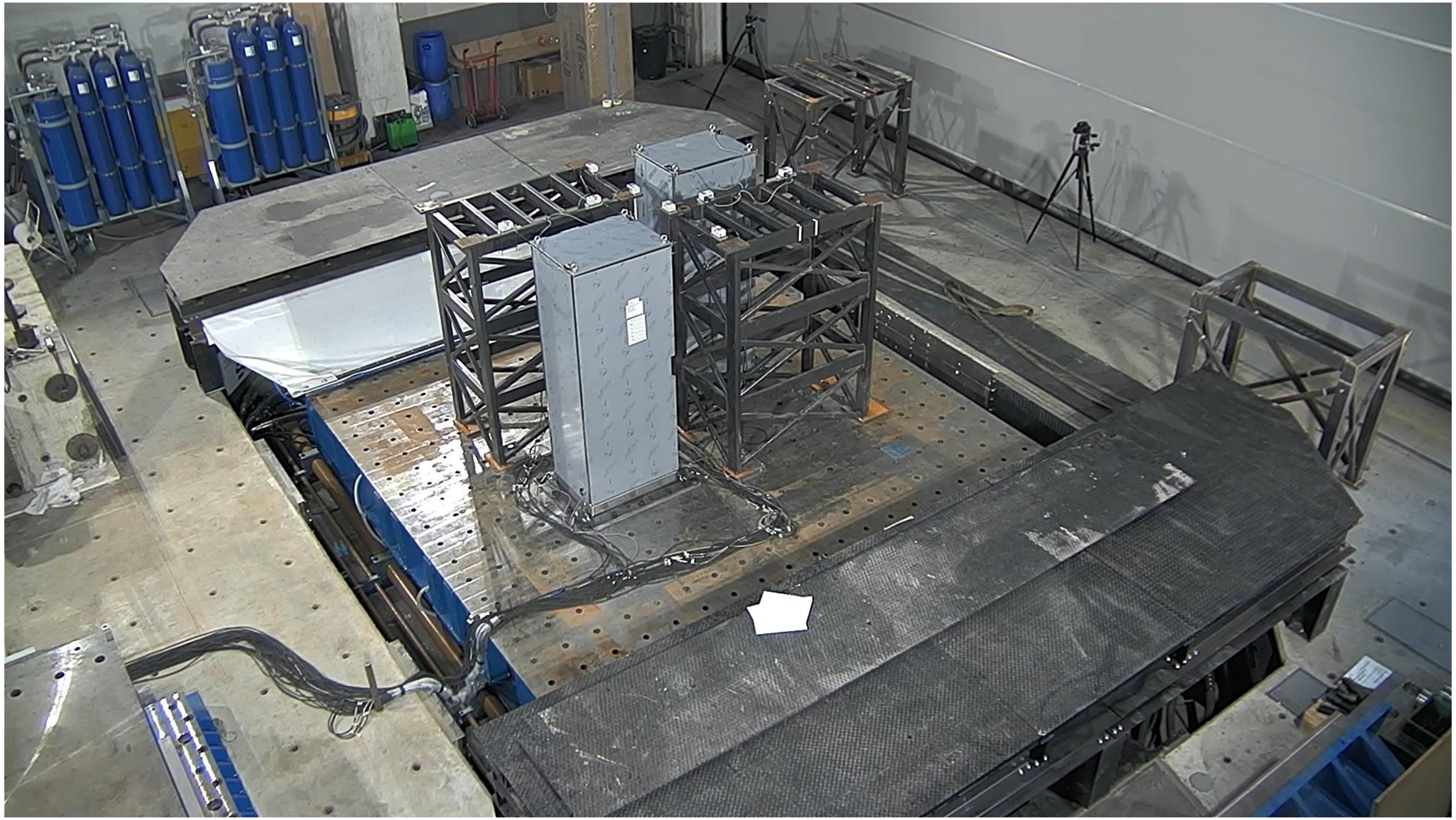

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SEISMIC DESIGN OF NSE – WHY?

- Integrating the design of non-structural elements (NSEs) into common design practice is nowadays a must
- Building system intended as a unique system that combines both structural skeleton/components and NSEs
- Non-trivial though because of interaction of different actors and professional roles in the design chain
- The Italian Building Code (NTC2018) requires minimum performance for building systems, including non-structural components/elements and distribution systems [§7.3.6]

Tab. 7.3.III – *Stati limite di elementi strutturali primari, elementi non strutturali e impianti*

STATI LIMITE		CU I	CU II			CU III e IV		
		ST	ST	NS	IM	ST	NS	IM(*)
SLE	*SLO*					RIG		FUN
	SLD	RIG	RIG			RES		
SLU	*SLV*	RES	RES	STA	STA	RES	STA	STA
	SLC		DUT(**)			DUT(**)		

(*) Per le sole CU III e IV, nella categoria Impianti ricadono anche gli arredi fissi.
(**) Nei casi esplicitamente indicati dalle presenti norme.

NON-STRUCTURAL COMPONENTS/ELEMENTS

Classification by type:

- Architectural components (claddings, ceilings, partitions)
- Mechanical, electrical and plumbing components and distribution systems
- Fixtures, furnishings and contents

Classification by behaviour:

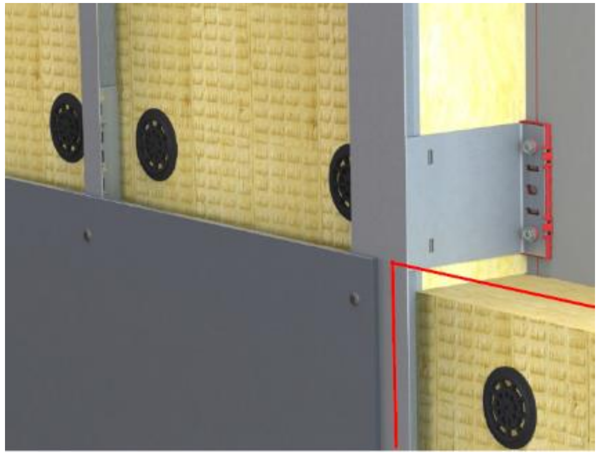
- Acceleration-sensitive
- Drift-sensitive
- Acceleration-and-drift-sensitive

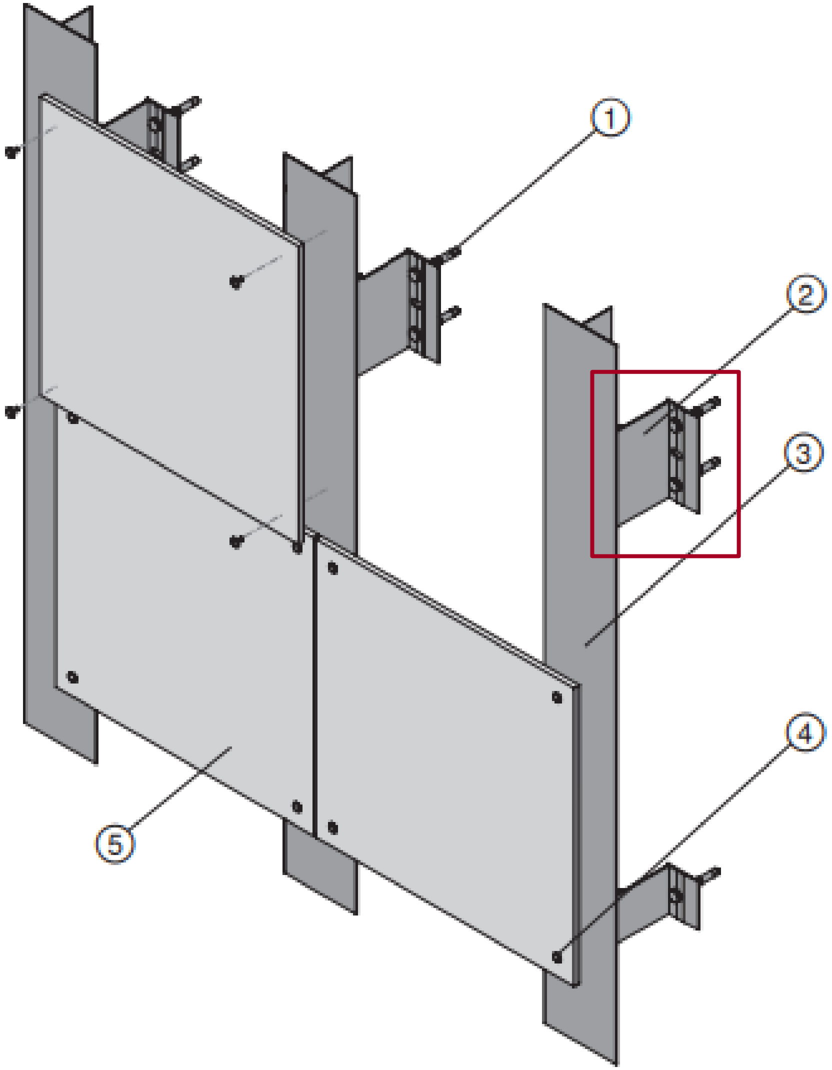
Ventilated façade

VENTILATED FAÇADE SYSTEMS

Components:

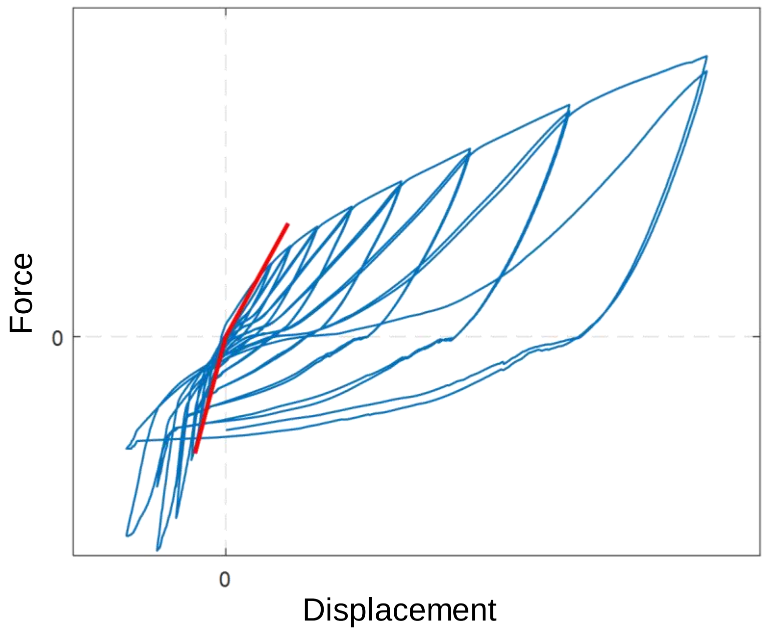
1. Base anchor
2. Bracket
3. Profile
4. Cladding fixing
5. Cladding elements

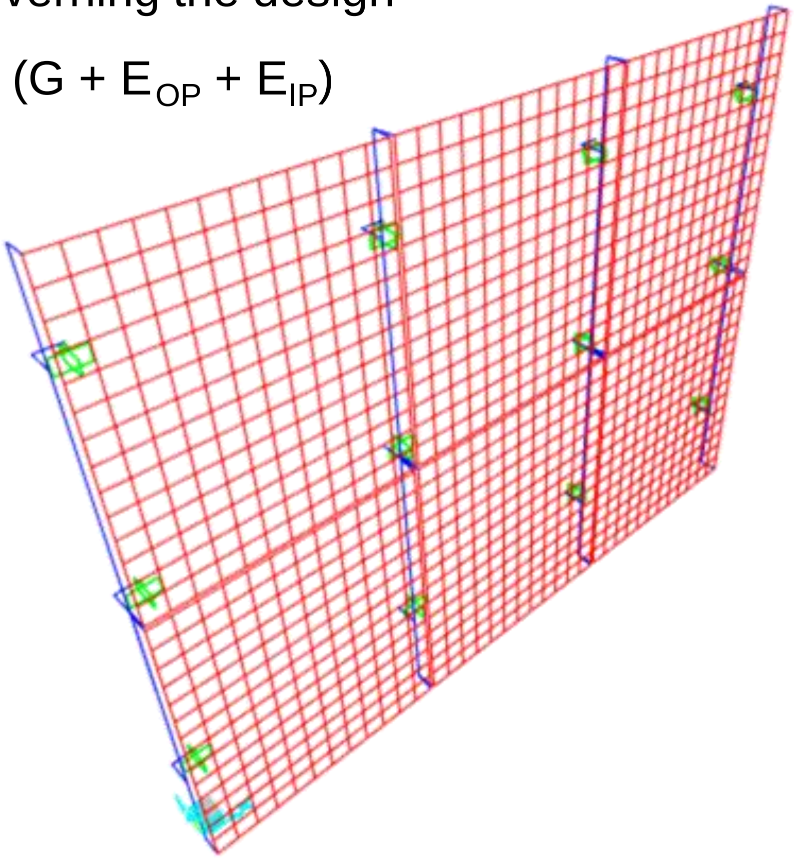




SEISMIC DESIGN THROUGH NUMERICAL MODELLING

- Experimental characterisation of components (and sub-assemblies) evaluating capacity (force and displacement), equivalent stiffness and, possibly, viscous damping
- Development of numerical modelling strategies able to correctly reproduce the actual behaviour
- Identification of constraints (displacement compatibility) possibly governing the design
- Finite element analysis and design under proper load combinations ($G + E_{OP} + E_{IP}$)



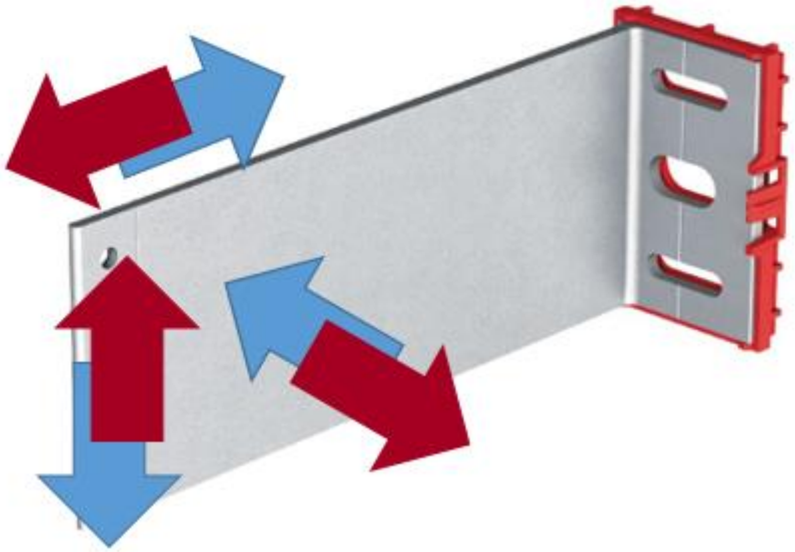


EXPERIMENTAL CHARACTERISATION

Instructions available for the testing of brackets under gravity and wind loads (EADs)

Seismic behaviour is not explicitly considered, implying no characterisation tests are foreseen for this type of loading. Specifically, indications are missing for what concerns:

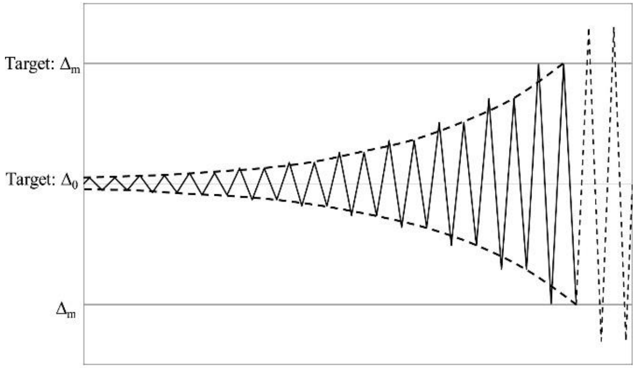
- Type (e.g. single component or assembly)
- Number of specimens
- Loading direction(s)
- Testing strategies (e.g. monotonic vs cyclic)
- Testing protocol (e.g. loading rate)

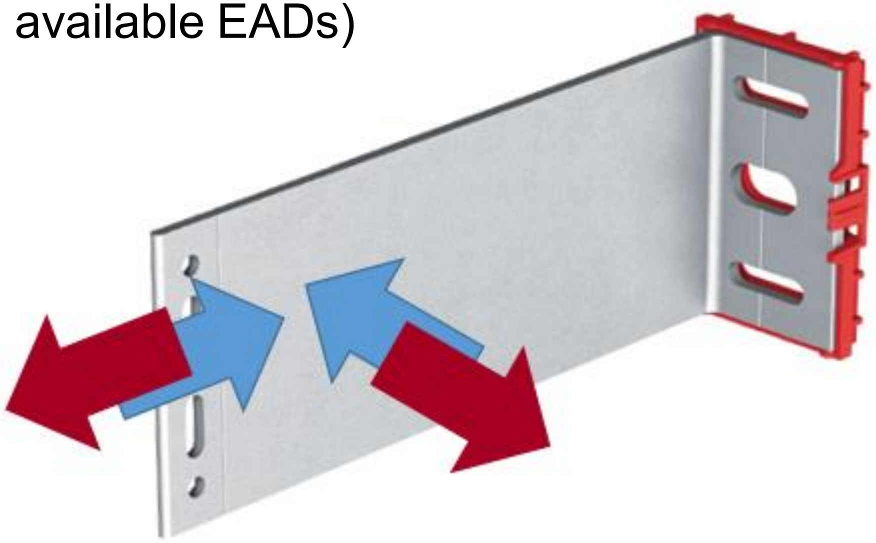


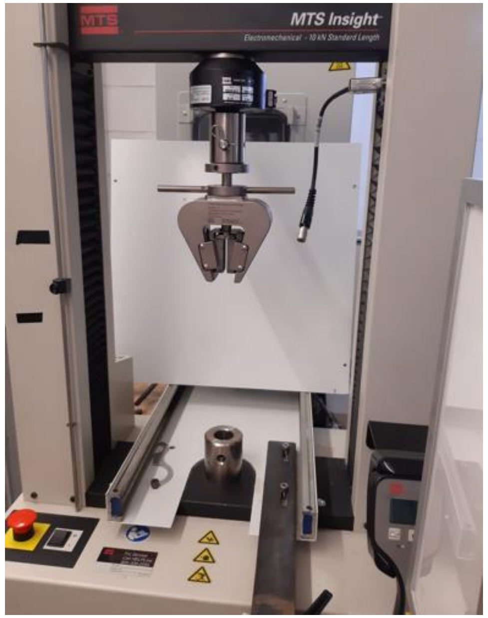
EXPERIMENTAL CHARACTERISATION

Tests were performed:

- On assemblies, with specimens featuring both bracket and L-profile with their actual connectors
- Using brackets characterised by different length and width/size
- Along directions other than gravity (i.e. horizontal in-plane and out-of-plane)
- Following general indications given by FEMA 461 for cyclic pseudo-static tests, i.e. 1 monotonic test + cyclic tests with loading protocol based on monotonic test results
- Loading rate ≤ 5 mm/min (according to available EADs)
- Using an universal testing machine
- And a set-up designed to avoid 2nd order effects, such as tension induced by lateral deflection



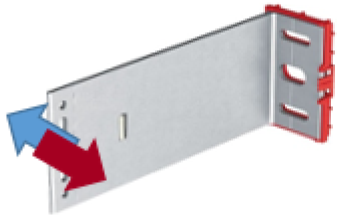


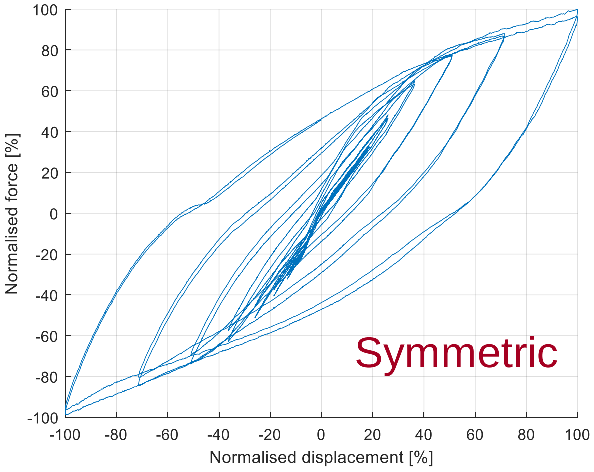


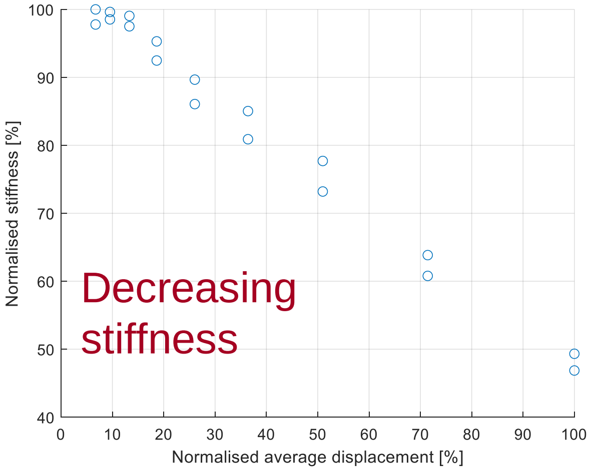
EXPERIMENTAL CHARACTERISATION

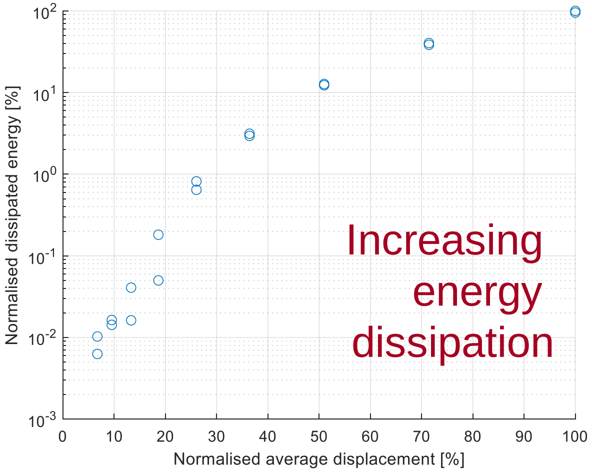
Mid-length/mid-size bracket specimen

- IP behaviour

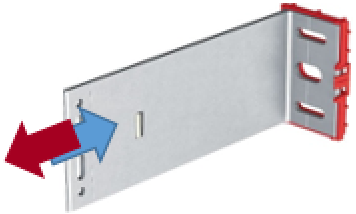


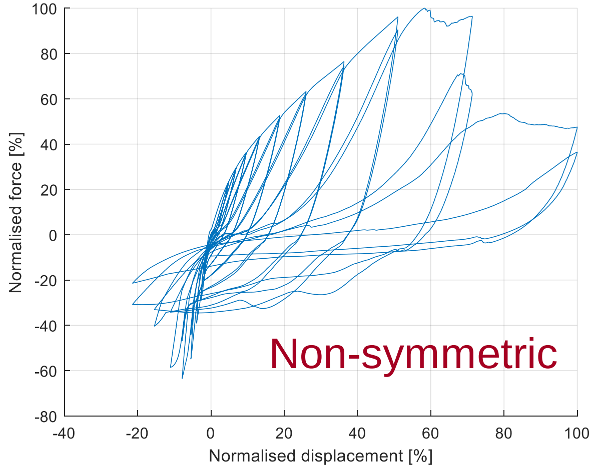


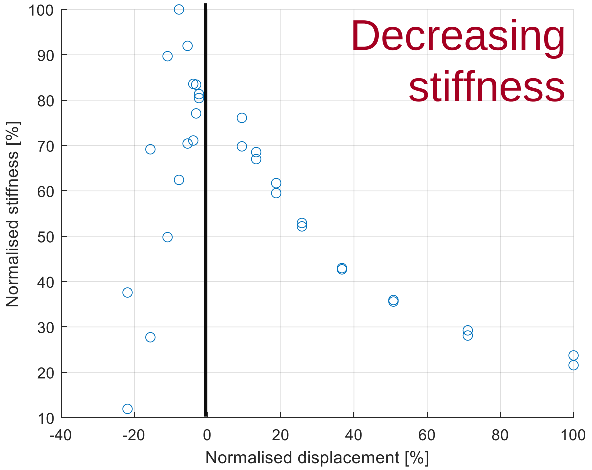


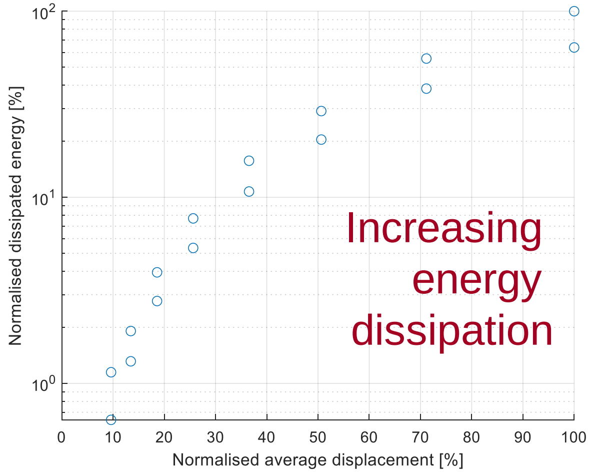


- OP behaviour



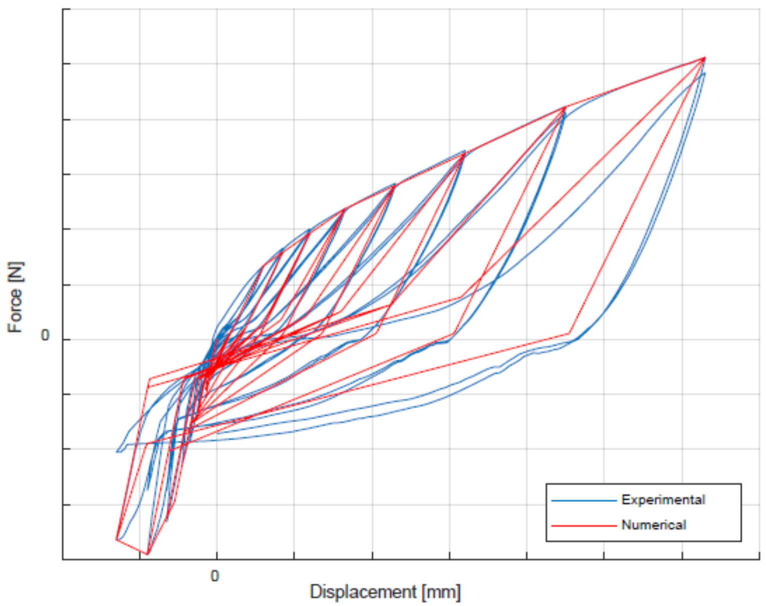


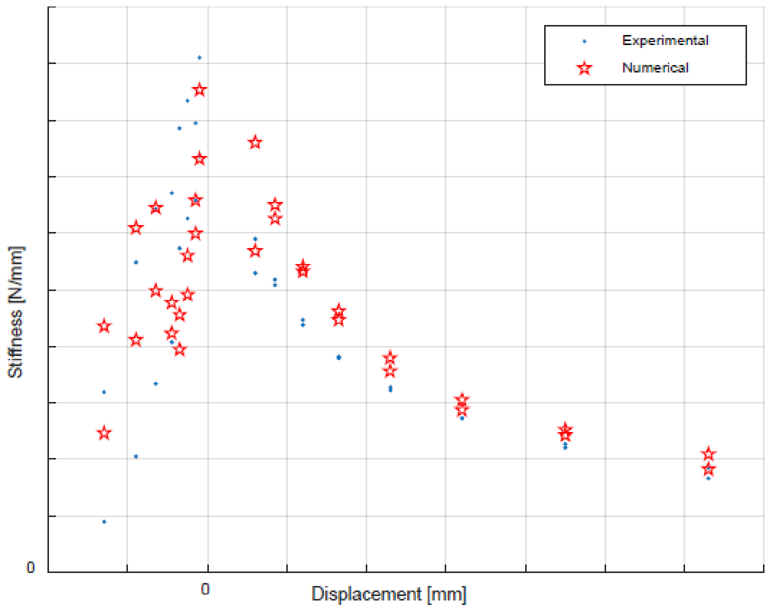


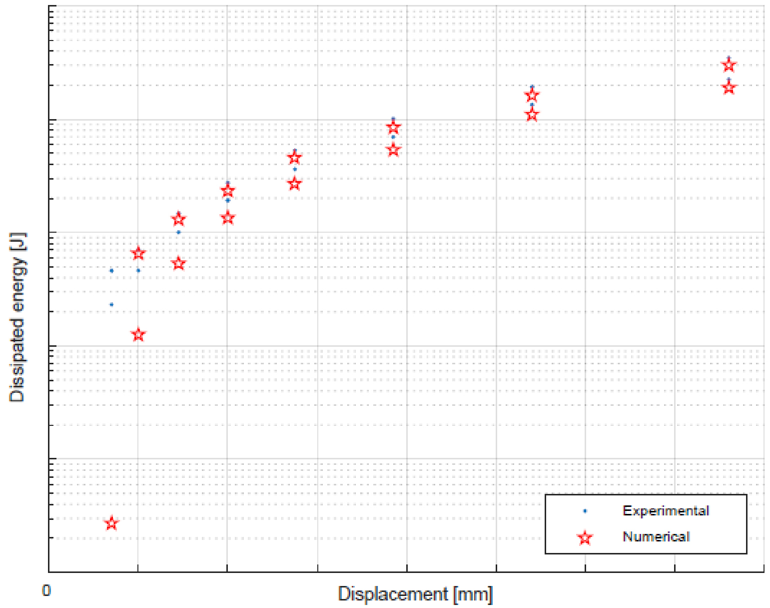


NUMERICAL MODELLING

- What kind of model, modelling and/or modelling strategy do we need?
- Linear or nonlinear? High-definition or not? A model should be as easy as possible, not easier…
- Experimental characterisation of components (and assemblies) targeting characterisation of equivalent stiffness and, possibly, viscous damping (w/ interaction of components)
- Full-scale lab testing and/or on-site dynamic identification for further validation







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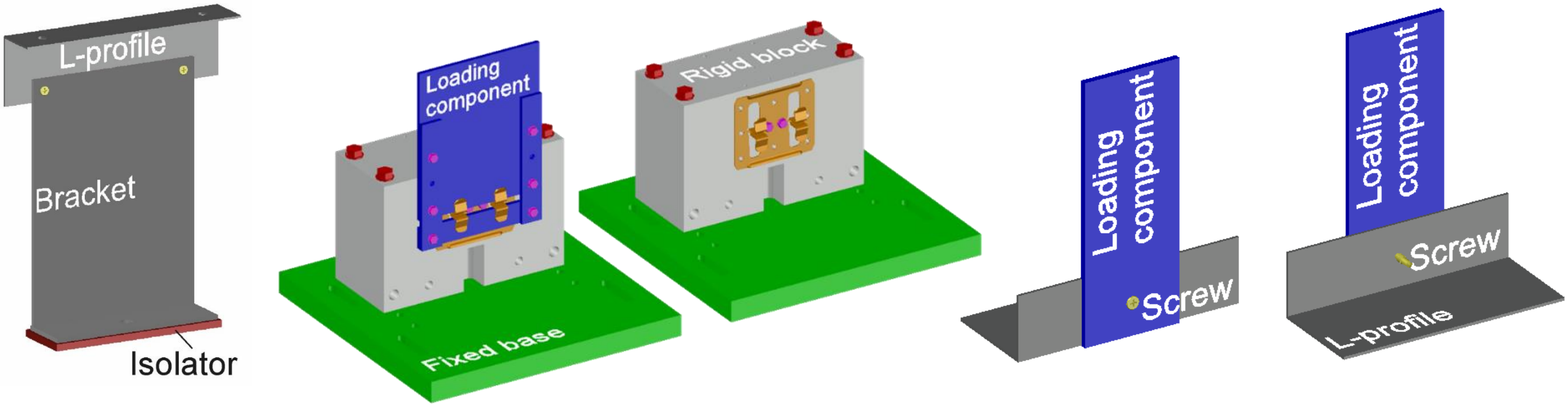
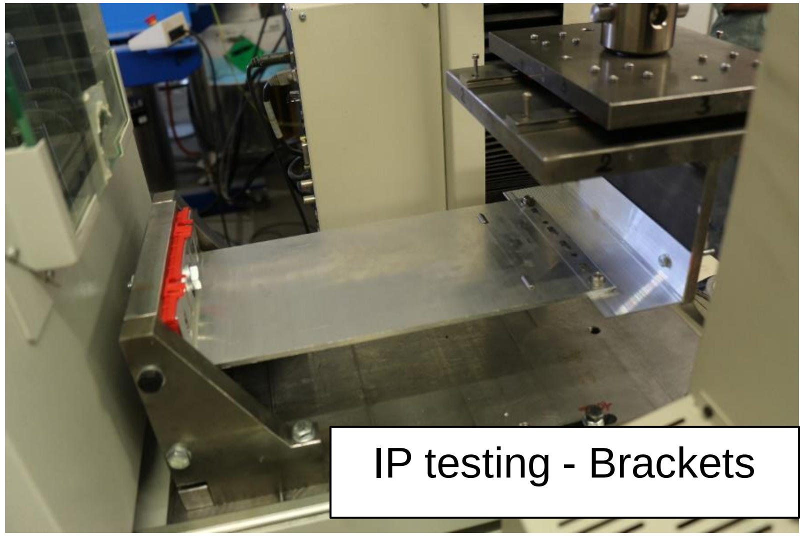
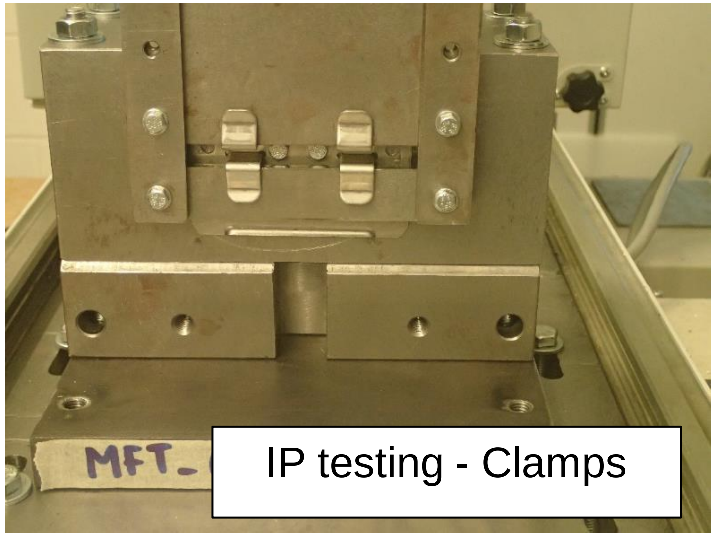
TESTING CAMPAIGN

- IP and OP testing of 3 components: brackets(+profile), clamps and screws
- Brackets: 3 sizes (S, M, L) and 5 lengths (40, 80, 140, 220, 300)
- Clamps: 6 types (M7,5, E7,5, B7,5, M9-12, E9-12, B9-12)
- Screws: type S-AD01LHSS
- 1M+5C (or 2M+5C) per each specimen, totalling 279 tests

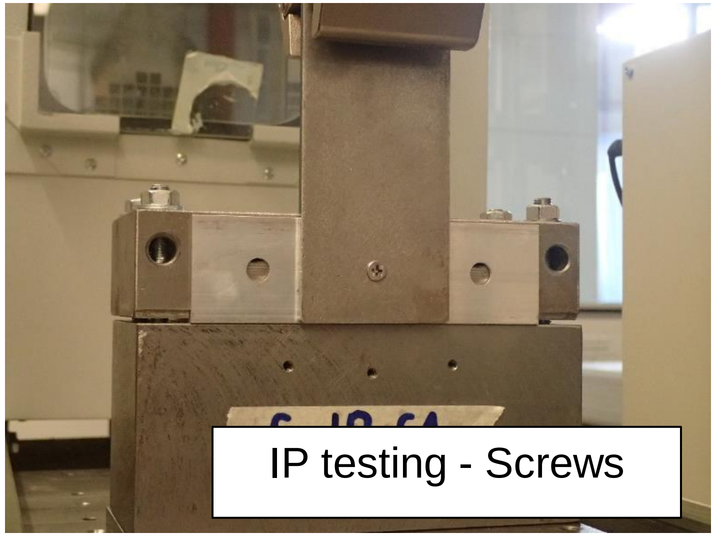


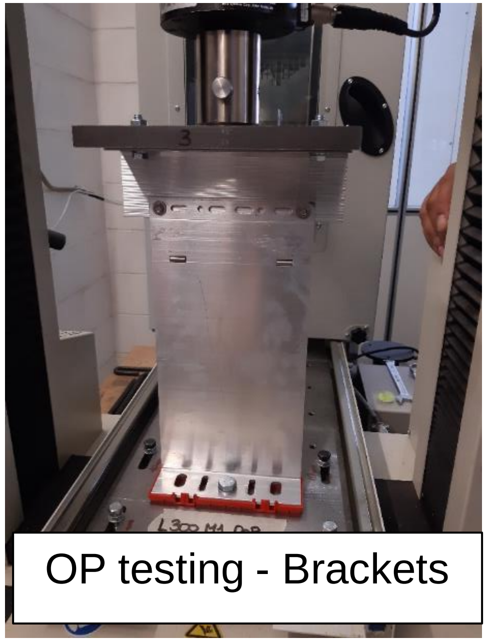
TEST SETUPS

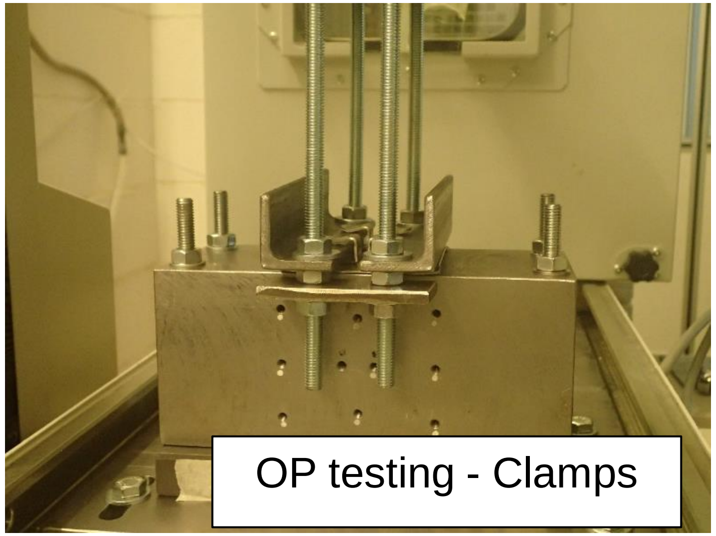

IP testing - Brackets

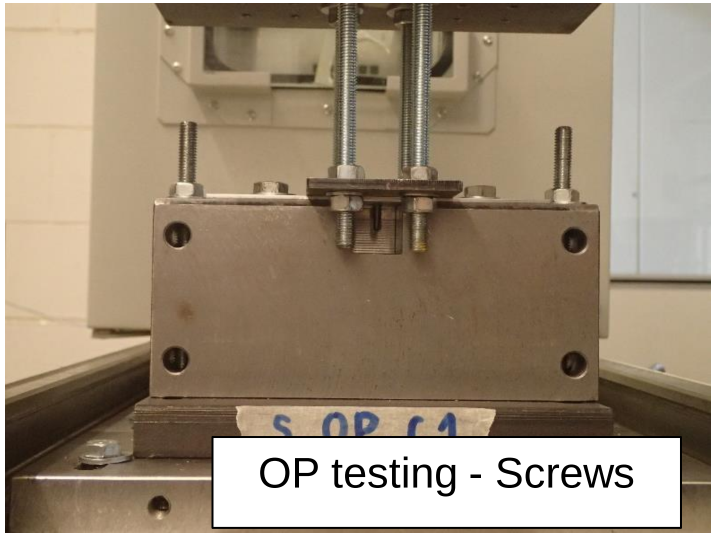


IP testing - Clamps


IP testing - Screws

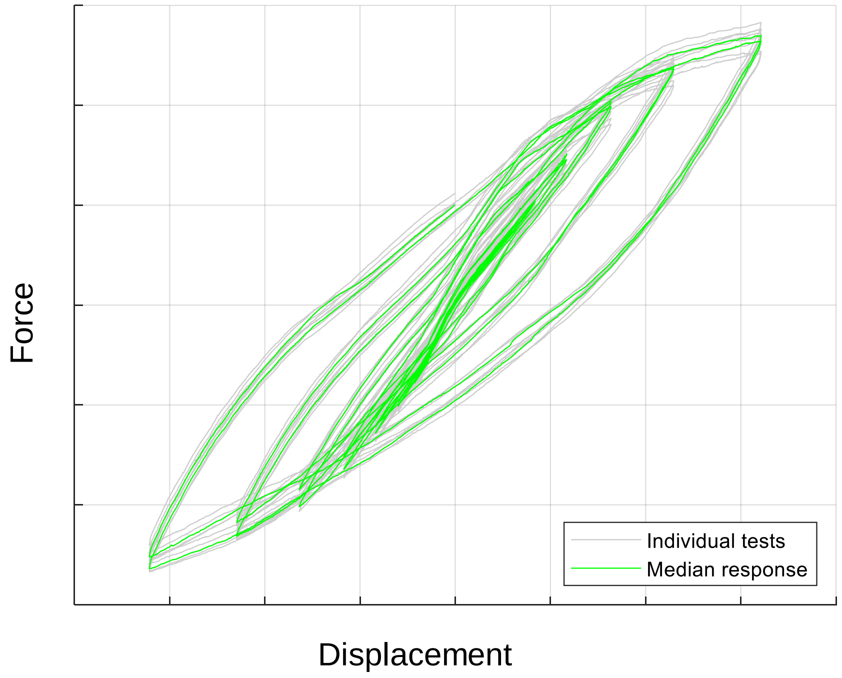

OP testing - Brackets

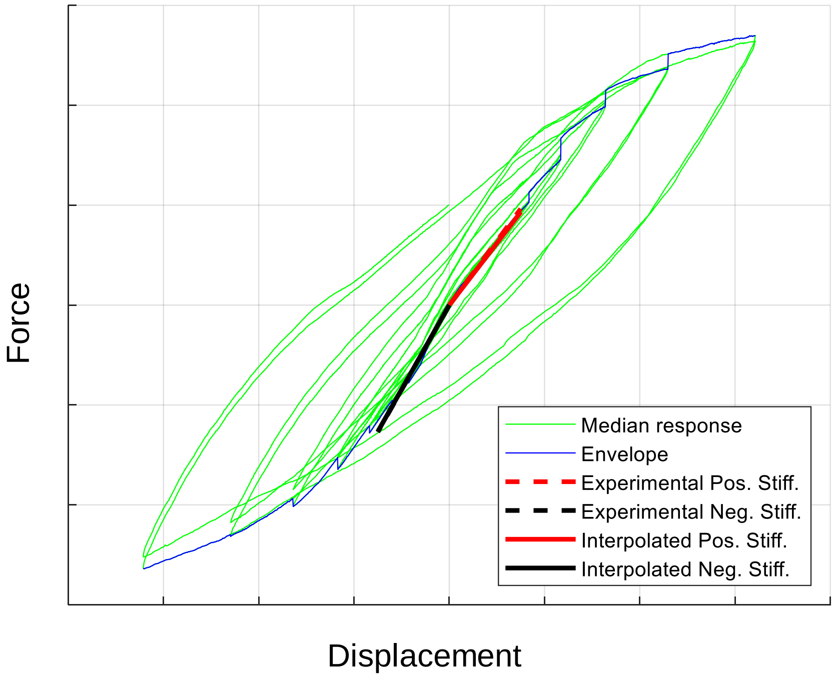

OP testing - Clamps


OP testing - Screws

TEST RESULTS AND DATA ANALYSIS

- IP testing of brackets (e.g. specimen type M140)
- Fairly symmetric; dissipation capacity; trends with size and length
- Interpolation and target displacement; ultimate/peak capacities
- Interpolated vs actual, positive and negative stiffness values





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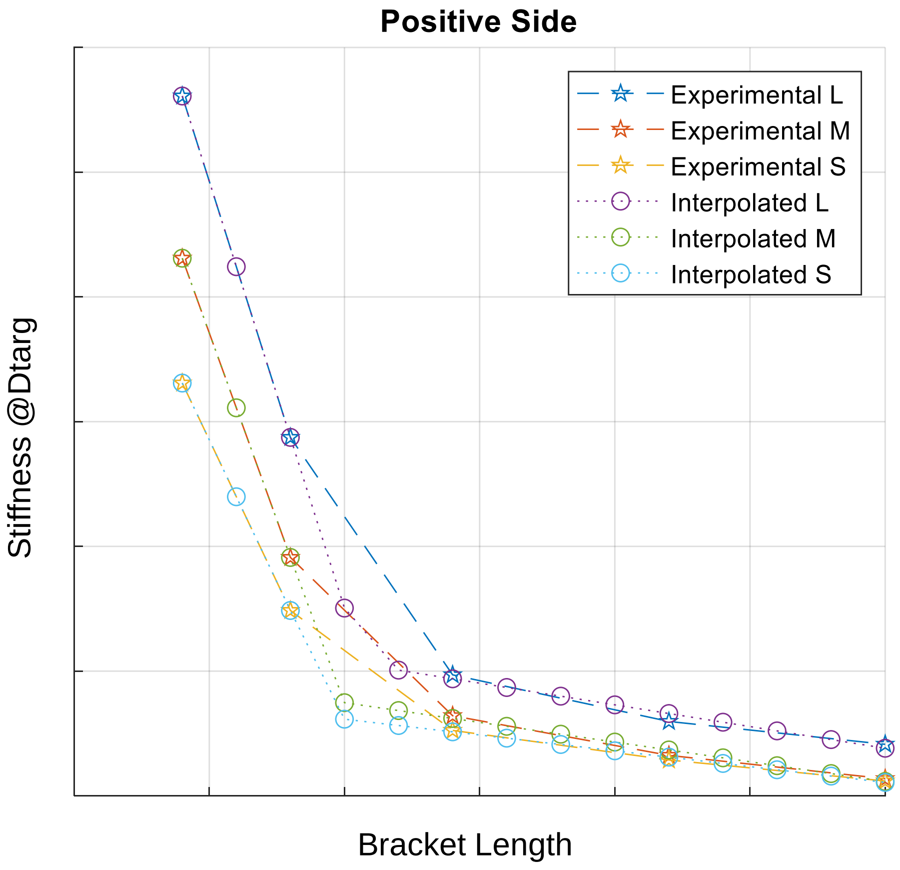
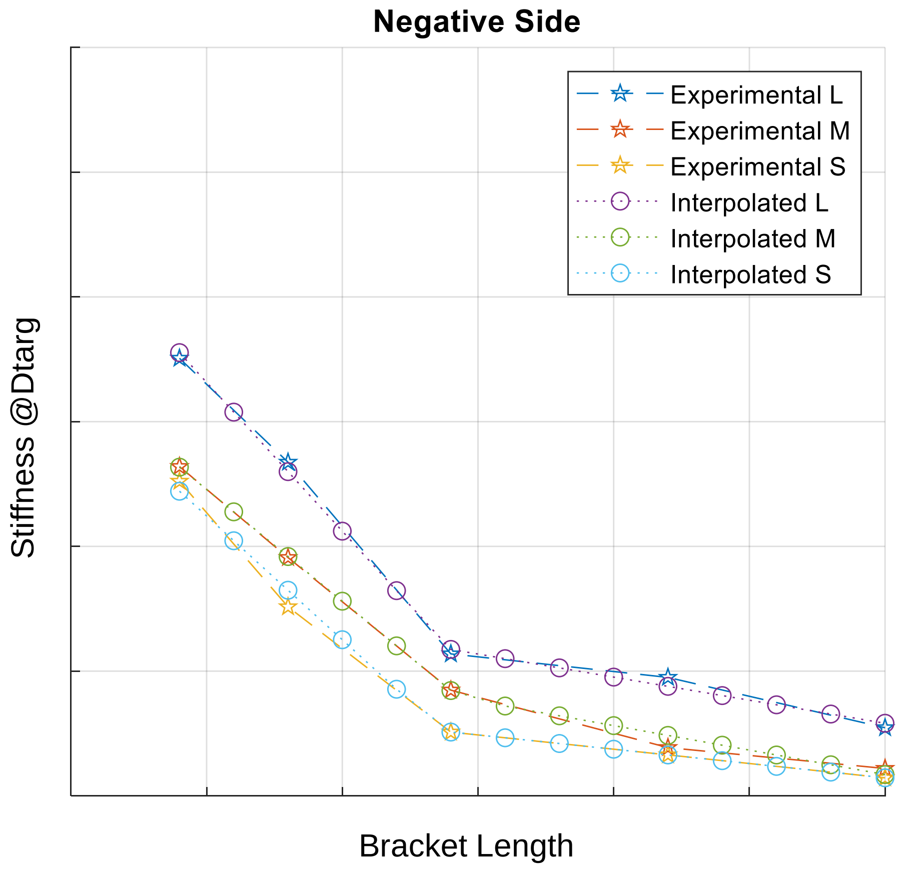
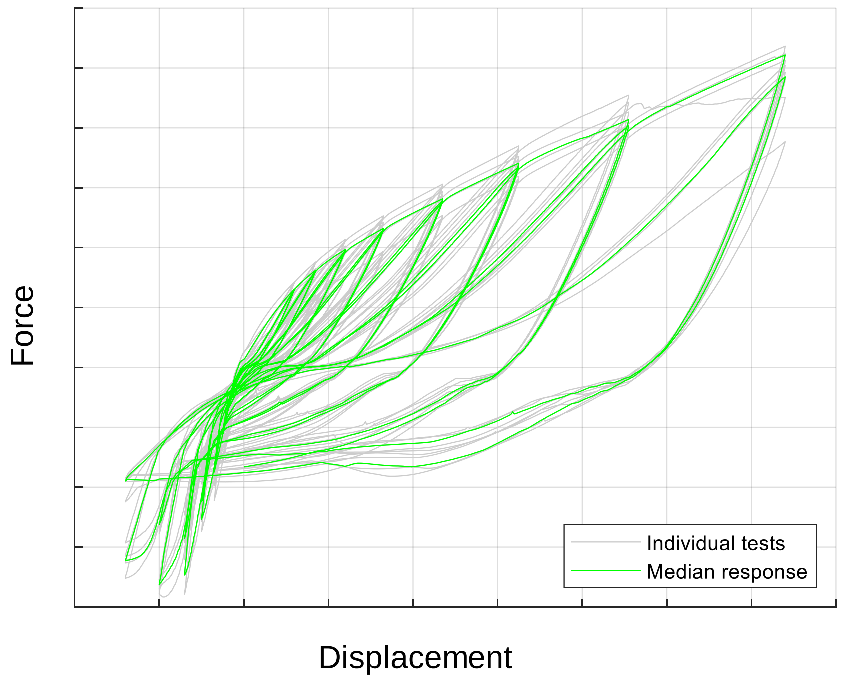
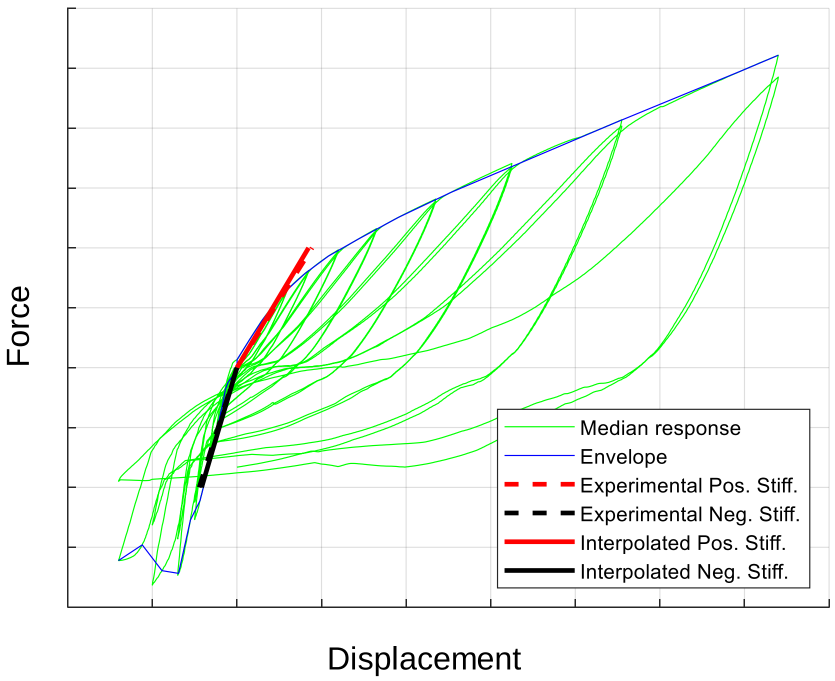




TEST RESULTS AND DATA ANALYSIS

- OP testing of brackets (e.g. specimen type M140)
- Highly asymmetric; dissipation capacity; trends with size and length
- Interpolation and target force; ultimate/peak capacities
- Interpolated vs actual, positive and negative stiffness values





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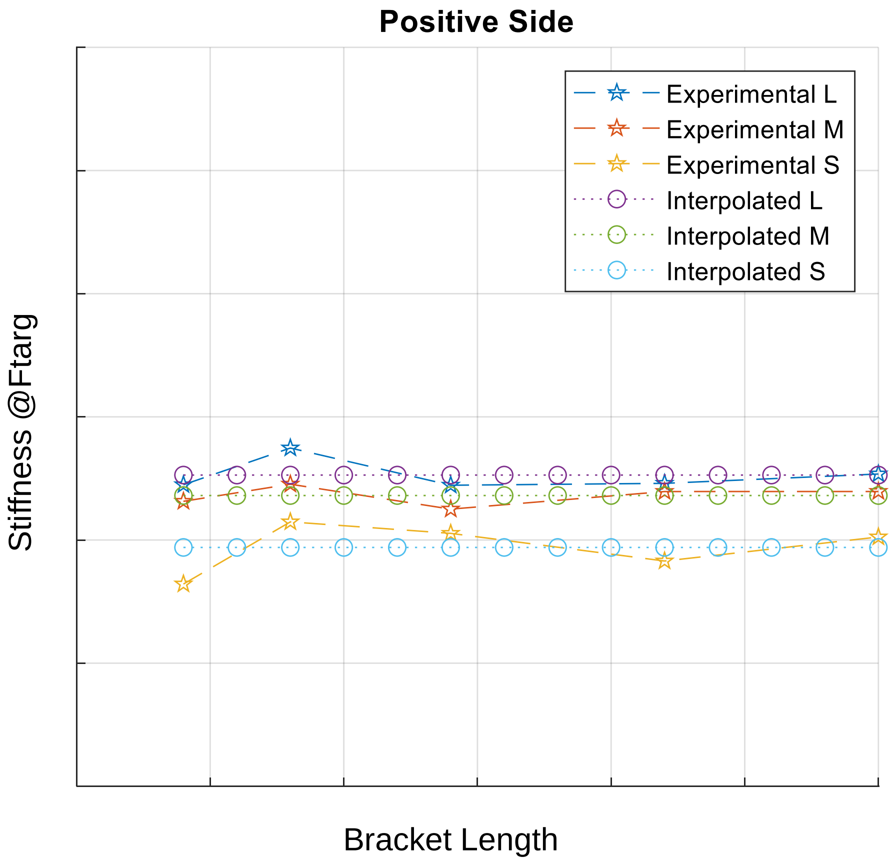
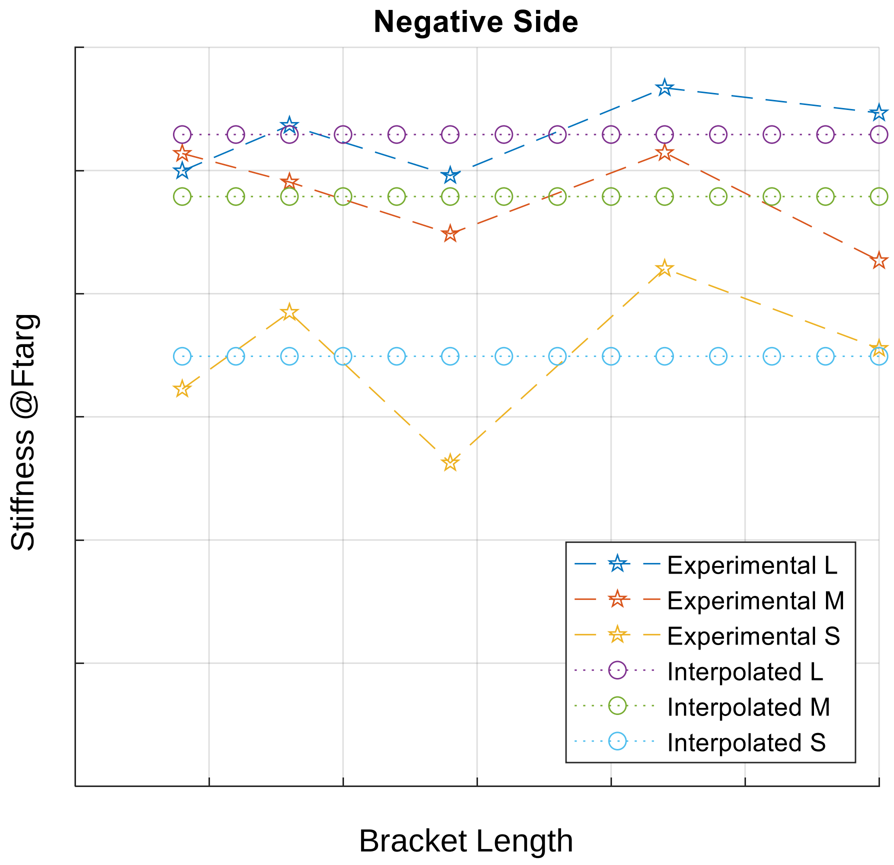
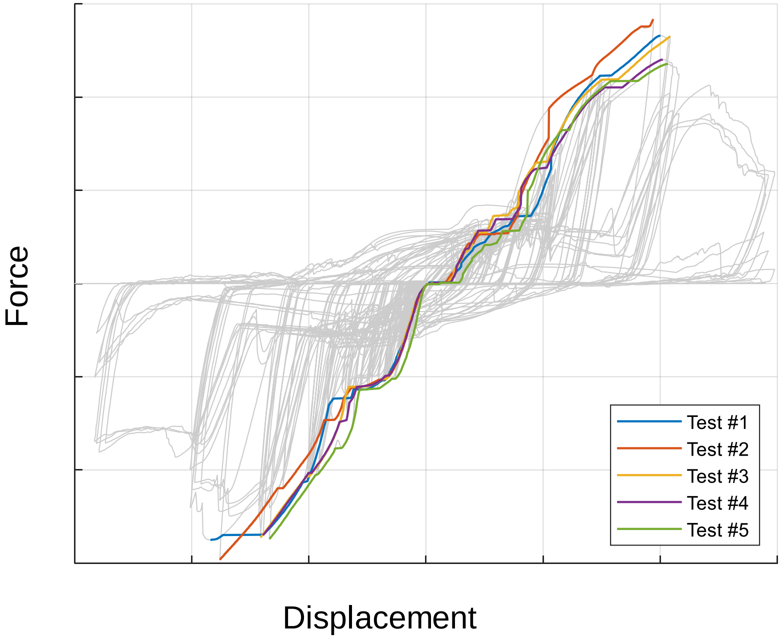
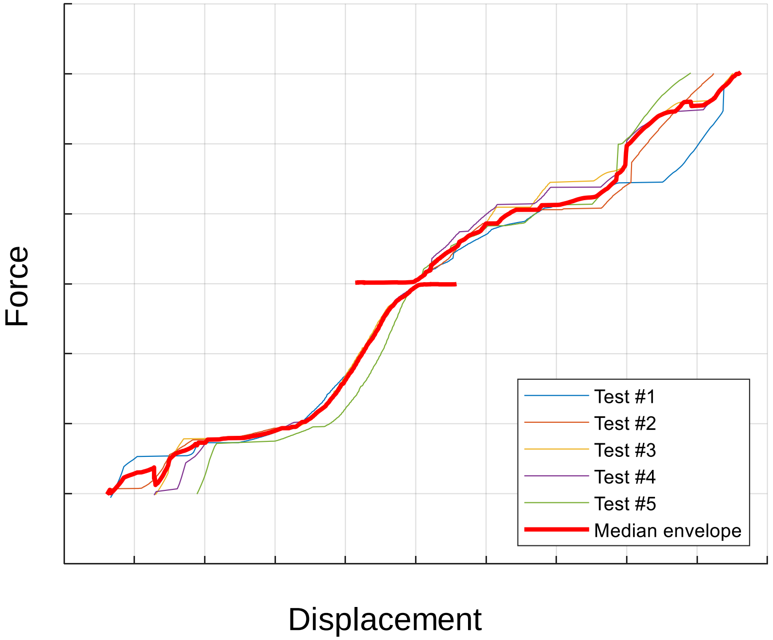




TEST RESULTS AND DATA ANALYSIS

- IP testing of clamps (e.g. specimen type CVM7,5)
- Clear damage mechanism; nonlinear behaviour and hook-to-hook contact
- Interpolation and target force; ultimate/peak capacities





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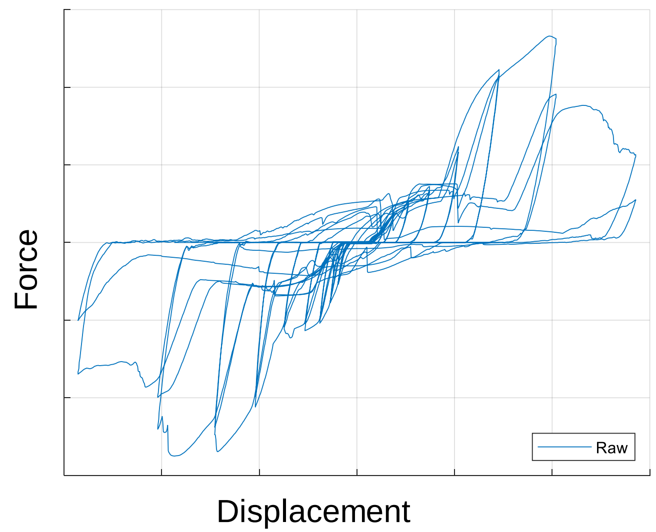

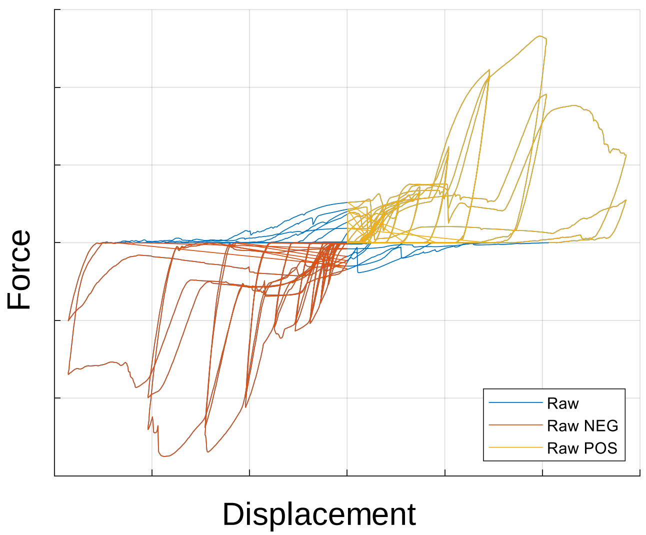

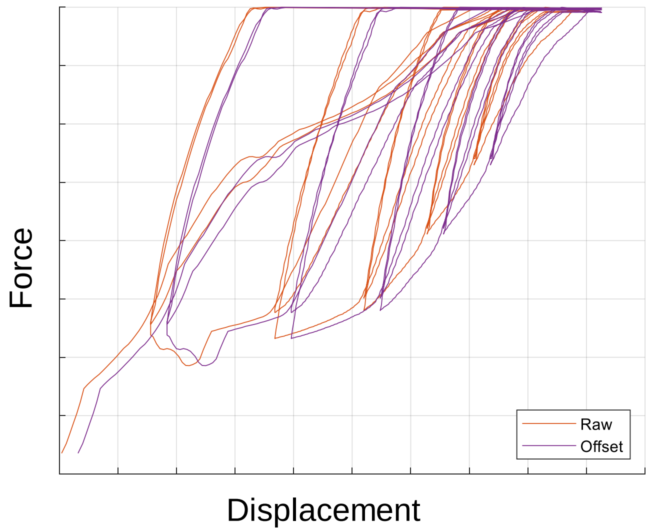

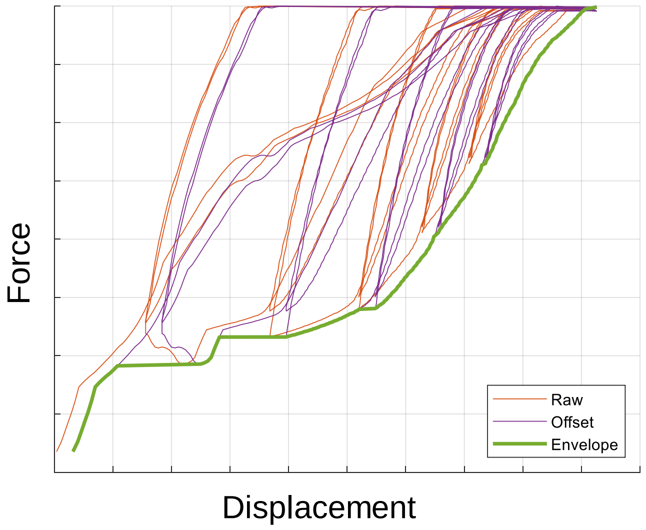

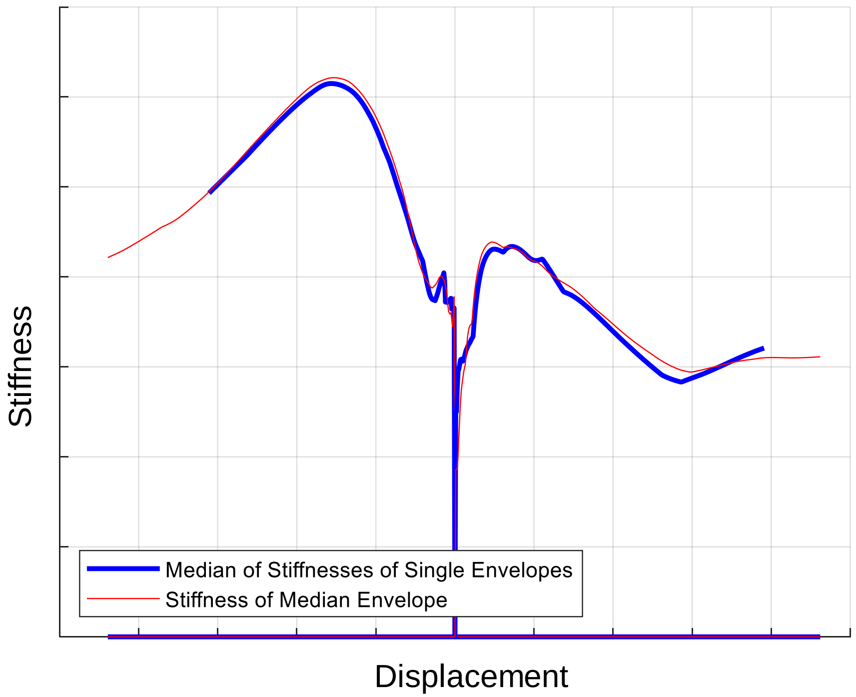

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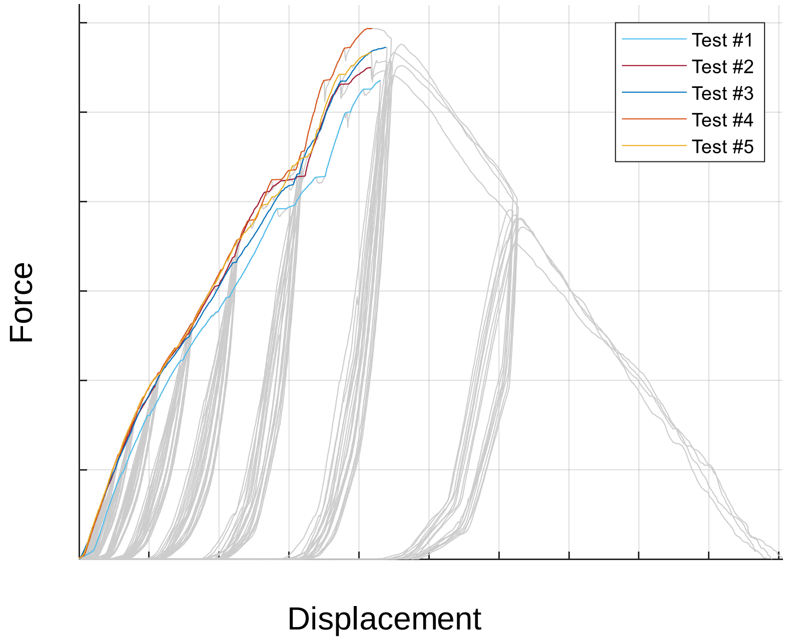

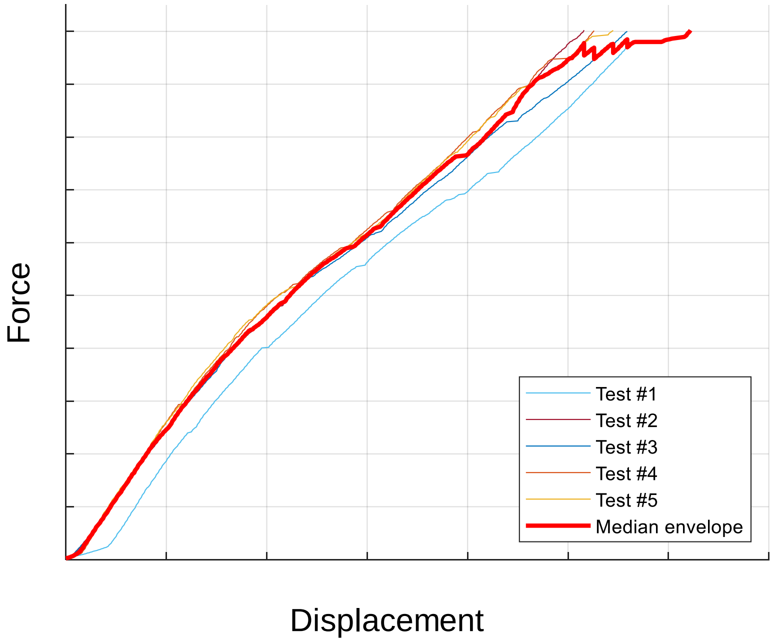

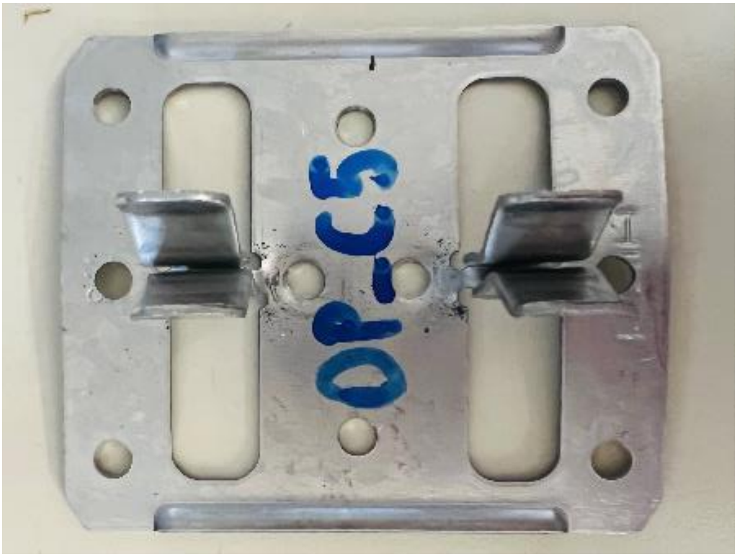

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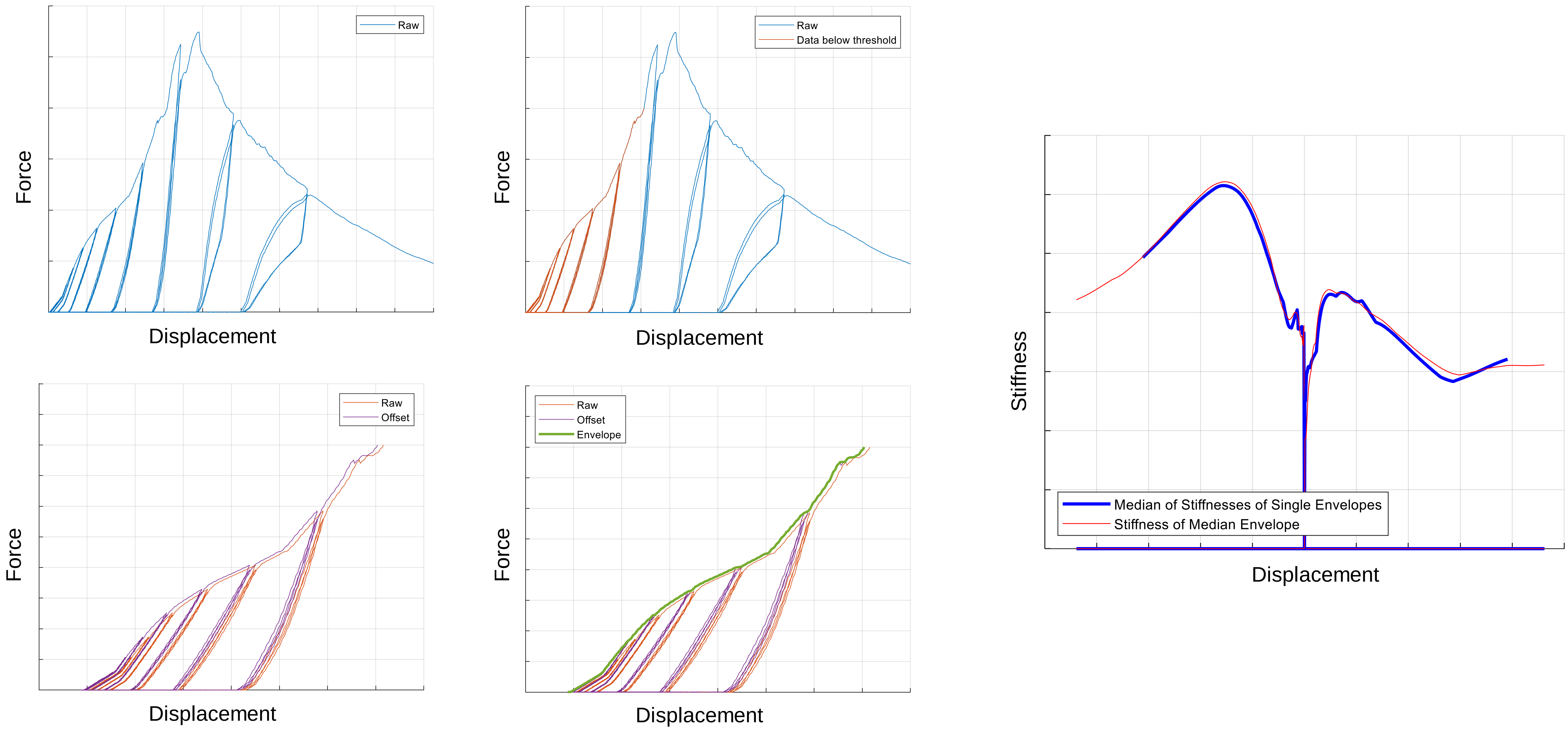
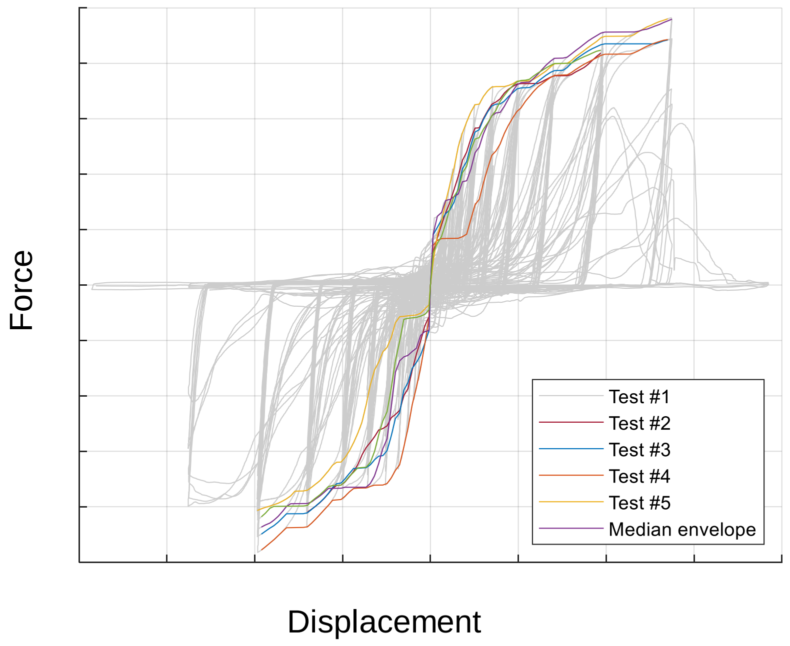
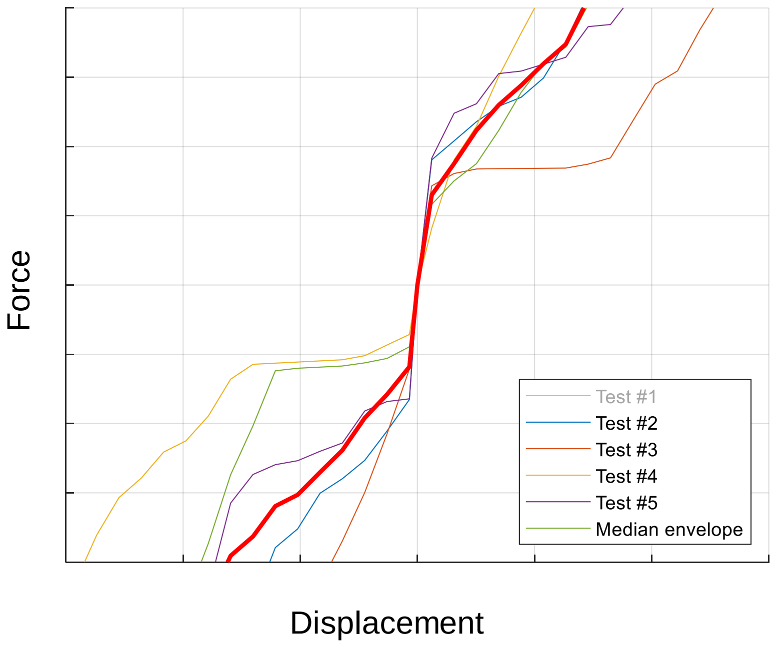


TEST RESULTS AND DATA ANALYSIS

- IP testing of screws (e.g. screw type S-AD01LHSS)
- Clear damage mechanism
- Rigid behaviour





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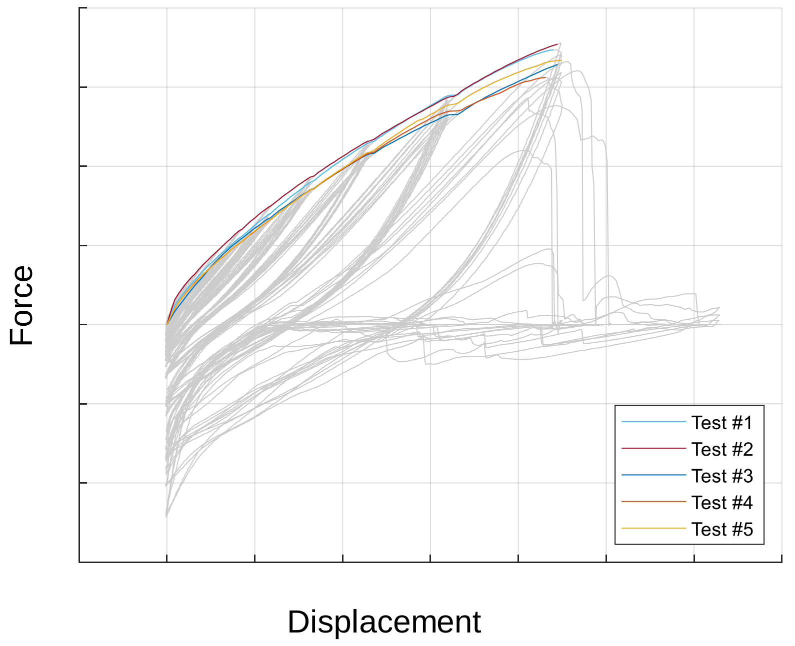
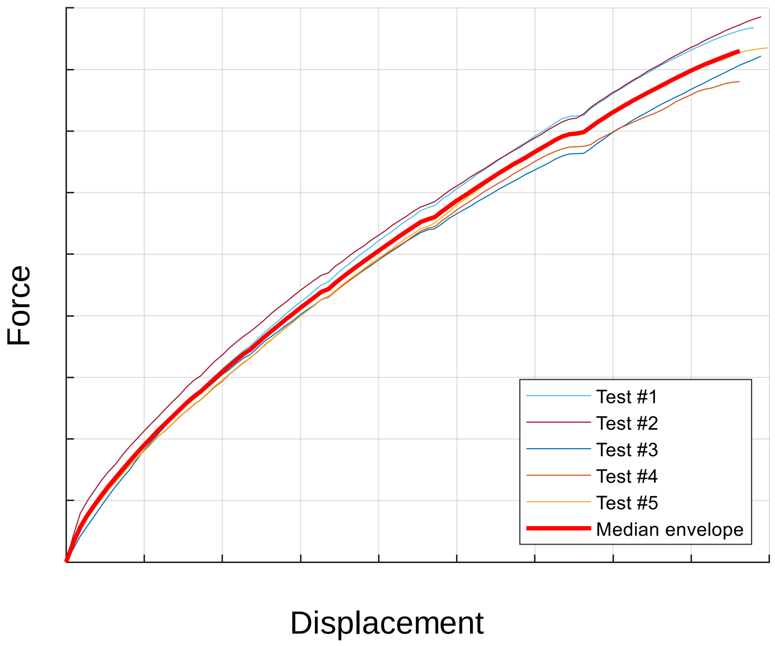
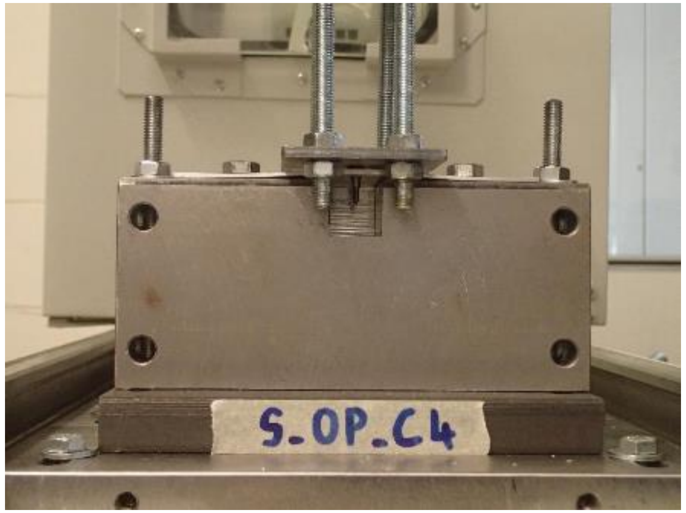


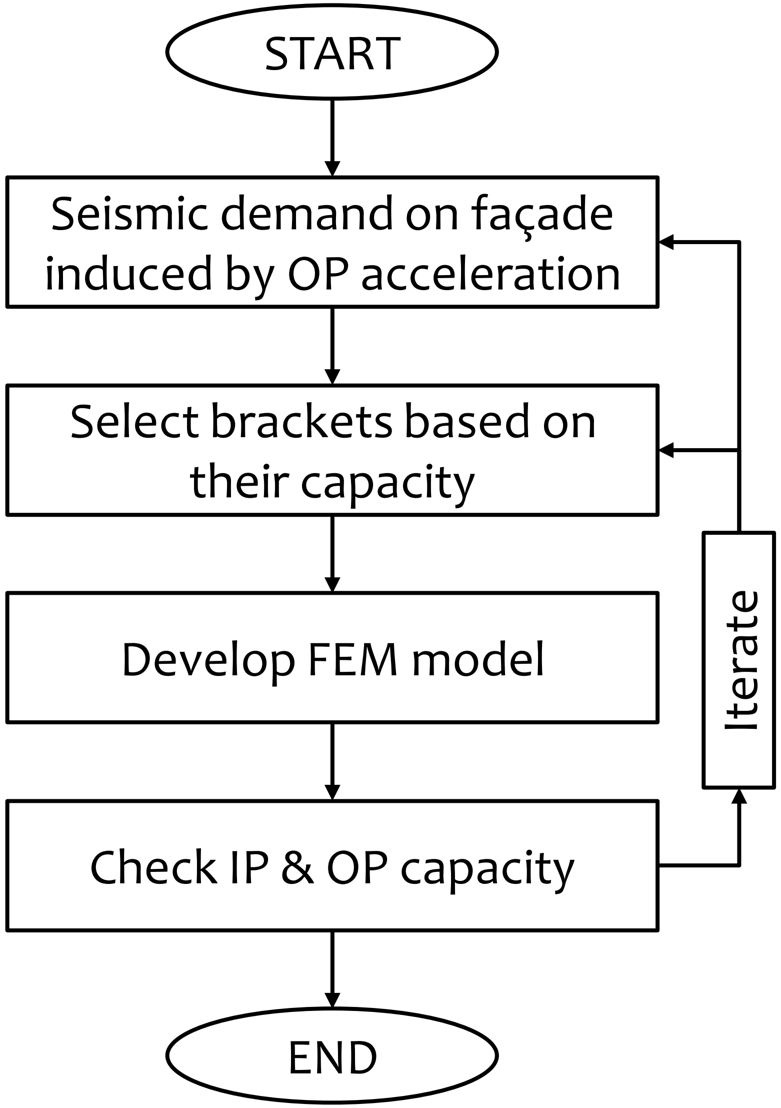


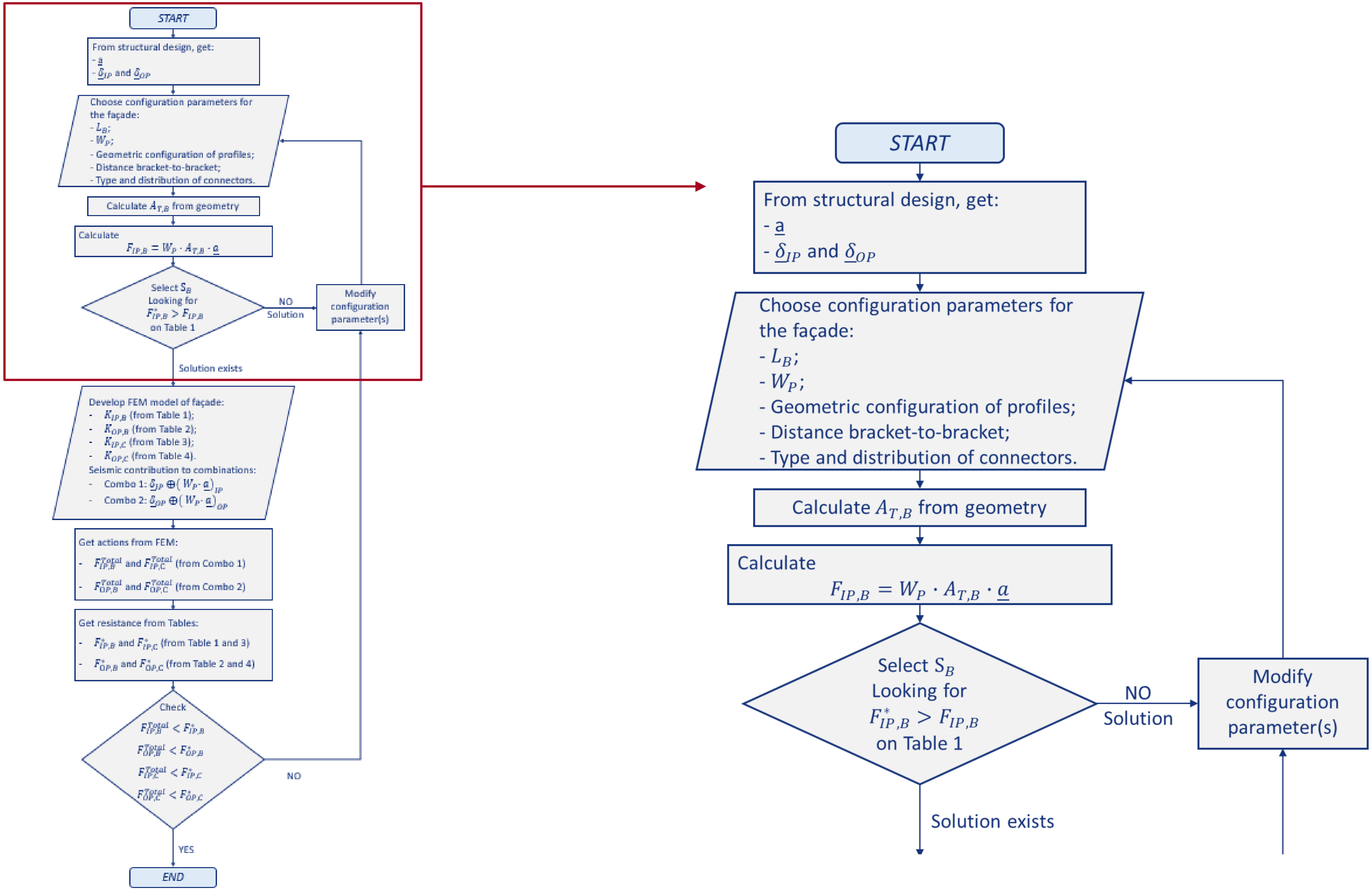


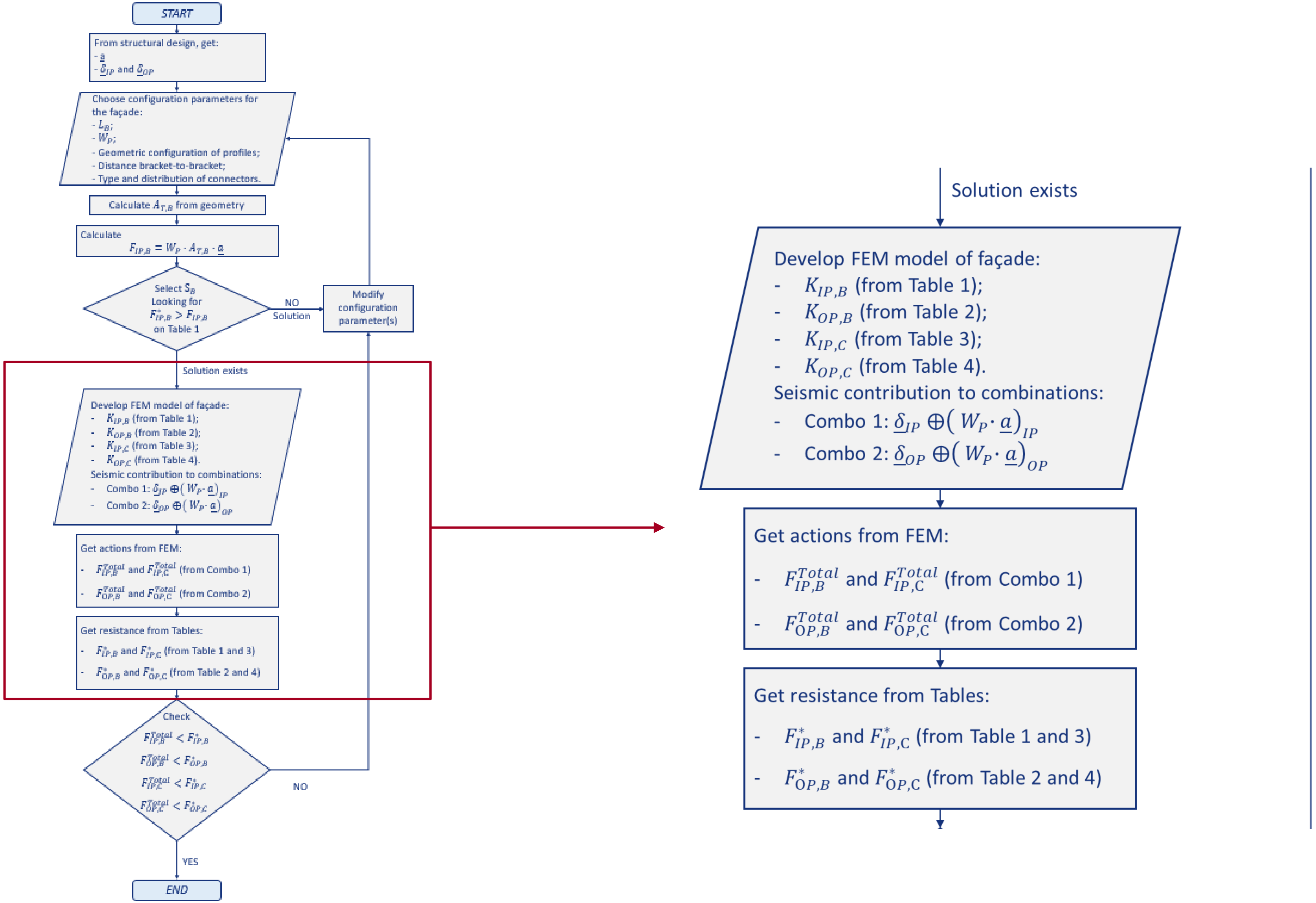
DESIGN METHODOLOGY

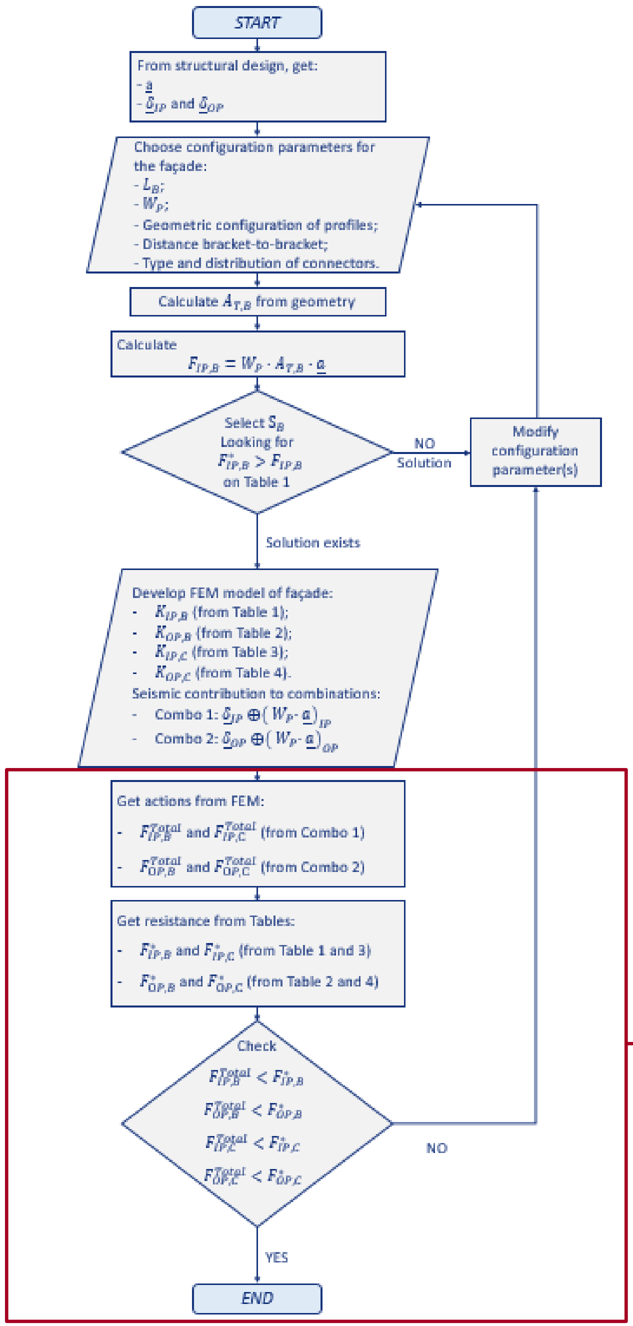
The proposed method is described by the following steps:

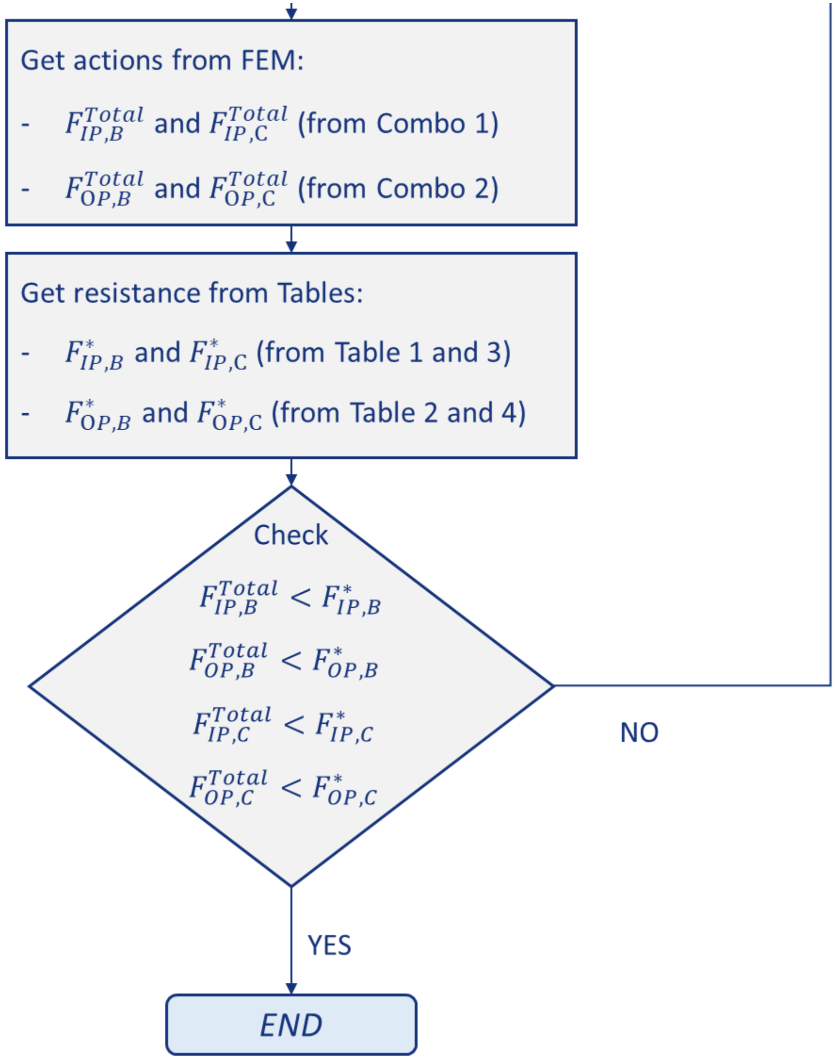
- Step 1: evaluate seismic demand on the façade (panel weight, tributary area, and floor acceleration).
- Step 2: select bracket size and length, according to geometry of the façade by checking IP capacity F* be greater than demand ($F^* > F_{IP}$).
- Step 3: develop FE model of the entire façade with calibrated stiffness for brackets K_b and impose inter-storey displacements δ suitable to the considered design limit state so as to obtain F_δ (i.e. inter-storey-displacement-driven actions on façade components).
- Step 4: check IP and OP capacity, and possibly iterate. Capacity of components (at target displacement) is derived through testing.




START
From structural design, get:
- $\underline{a}$
- $\underline{\delta}_{IP}$ and $\underline{\delta}_{OP}$
Choose configuration parameters for the façade:
- L_B;
- W_P;
- Geometric configuration of profiles;
- Distance bracket-to-bracket;
- Type and distribution of connectors.
Calculate $A_{T,B}$ from geometry
Calculate $F_{IP,B} = W_P \cdot A_{T,B} \cdot \underline{a}$
Select S_B Looking for $F^*_{IP,B} > F_{IP,B}$ on Table 1
NO Solution
Modify configuration parameter(s)
Solution exists
Develop FEM model of façade:
- $K_{IP,B}$ (from Table 1);
- $K_{OP,B}$ (from Table 2);
- $K_{IP,C}$ (from Table 3);
- $K_{OP,C}$ (from Table 4).
Seismic contribution to combinations:
- Combo 1: $\underline{\delta}_{IP} \oplus (W_P \cdot \underline{a})_{IP}$
- Combo 2: $\underline{\delta}_{OP} \oplus (W_P \cdot \underline{a})_{OP}$
Get actions from FEM:
- $F^{Total}_{IP,B}$ and $F^{Total}_{IP,C}$ (from Combo 1)
- $F^{Total}_{OP,B}$ and $F^{Total}_{OP,C}$ (from Combo 2)
Get resistance from Tables:
- $F^*_{IP,B}$ and $F^*_{IP,C}$ (from Table 1 and 3)
- $F^*_{OP,B}$ and $F^*_{OP,C}$ (from Table 2 and 4)
Check
$F^{Total}_{IP,B} < F^*_{IP,B}$
$F^{Total}_{OP,B} < F^*_{OP,B}$
$F^{Total}_{IP,C} < F^*_{IP,C}$
$F^{Total}_{OP,C} < F^*_{OP,C}$
NO
YES
END


START
From structural design, get:
- $\underline{a}$
- δ_{IP} and δ_{OP}
Choose configuration parameters for the façade:
- L_B;
- W_P;
- Geometric configuration of profiles;
- Distance bracket-to-bracket;
- Type and distribution of connectors.
Calculate $A_{T,B}$ from geometry
Calculate $F_{IP,B} = W_P \cdot A_{T,B} \cdot \underline{a}$
Select S_B Looking for $F^*_{IP,B} > F_{IP,B}$ on Table 1
NO Solution
Modify configuration parameter(s)
Solution exists
Develop FEM model of façade:
- $K_{IP,B}$ (from Table 1);
- $K_{OP,B}$ (from Table 2);
- $K_{IP,C}$ (from Table 3);
- $K_{OP,C}$ (from Table 4).
Seismic contribution to combinations:
- Combo 1: $\delta_{IP} \oplus (W_P \cdot \underline{a})_{IP}$
- Combo 2: $\delta_{OP} \oplus (W_P \cdot \underline{a})_{OP}$
Get actions from FEM:
- $F^{Total}_{IP,B}$ and $F^{Total}_{IP,C}$ (from Combo 1)
- $F^{Total}_{OP,B}$ and $F^{Total}_{OP,C}$ (from Combo 2)
Get resistance from Tables:
- $F^*_{IP,B}$ and $F^*_{IP,C}$ (from Table 1 and 3)
- $F^*_{OP,B}$ and $F^*_{OP,C}$ (from Table 2 and 4)
Check
$F^{Total}_{IP,B} < F^*_{IP,B}$
$F^{Total}_{OP,B} < F^*_{OP,B}$
$F^{Total}_{IP,C} < F^*_{IP,C}$
$F^{Total}_{OP,C} < F^*_{OP,C}$
NO
YES
END
Solution exists
Develop FEM model of façade:
- $K_{IP,B}$ (from Table 1);
- $K_{OP,B}$ (from Table 2);
- $K_{IP,C}$ (from Table 3);
- $K_{OP,C}$ (from Table 4).
Seismic contribution to combinations:
- Combo 1: $\delta_{IP} \oplus (W_P \cdot \underline{a})_{IP}$
- Combo 2: $\delta_{OP} \oplus (W_P \cdot \underline{a})_{OP}$
Get actions from FEM:
- $F^{Total}_{IP,B}$ and $F^{Total}_{IP,C}$ (from Combo 1)
- $F^{Total}_{OP,B}$ and $F^{Total}_{OP,C}$ (from Combo 2)
Get resistance from Tables:
- $F^*_{IP,B}$ and $F^*_{IP,C}$ (from Table 1 and 3)
- $F^*_{OP,B}$ and $F^*_{OP,C}$ (from Table 2 and 4)


START
From structural design, get:
- $\underline{a}$
- $\underline{\delta}_{IP}$ and $\underline{\delta}_{OP}$
Choose configuration parameters for the façade:
- L_B;
- W_P;
- Geometric configuration of profiles;
- Distance bracket-to-bracket;
- Type and distribution of connectors.
Calculate $A_{T,B}$ from geometry
Calculate $F_{IP,B} = W_P \cdot A_{T,B} \cdot \underline{a}$
Select S_B Looking for $F^*_{IP,B} > F_{IP,B}$ on Table 1
NO Solution
Modify configuration parameter(s)
Solution exists
Develop FEM model of façade:
- $K_{IP,B}$ (from Table 1);
- $K_{OP,B}$ (from Table 2);
- $K_{IP,C}$ (from Table 3);
- $K_{OP,C}$ (from Table 4).
Seismic contribution to combinations:
- Combo 1: $\underline{\delta}_{IP} \oplus (W_P \cdot \underline{a})_{IP}$
- Combo 2: $\underline{\delta}_{OP} \oplus (W_P \cdot \underline{a})_{OP}$
Get actions from FEM:
- $F^{Total}_{IP,B}$ and $F^{Total}_{IP,C}$ (from Combo 1)
- $F^{Total}_{OP,B}$ and $F^{Total}_{OP,C}$ (from Combo 2)
Get resistance from Tables:
- $F^*_{IP,B}$ and $F^*_{IP,C}$ (from Table 1 and 3)
- $F^*_{OP,B}$ and $F^*_{OP,C}$ (from Table 2 and 4)
Check
$F^{Total}_{IP,B} < F^*_{IP,B}$
$F^{Total}_{OP,B} < F^*_{OP,B}$
$F^{Total}_{IP,C} < F^*_{IP,C}$
$F^{Total}_{OP,C} < F^*_{OP,C}$
NO
YES
END


Get actions from FEM:
- $F^{Total}_{IP,B}$ and $F^{Total}_{IP,C}$ (from Combo 1)
- $F^{Total}_{OP,B}$ and $F^{Total}_{OP,C}$ (from Combo 2)
Get resistance from Tables:
- $F^*_{IP,B}$ and $F^*_{IP,C}$ (from Table 1 and 3)
- $F^*_{OP,B}$ and $F^*_{OP,C}$ (from Table 2 and 4)
Check
$F^{Total}_{IP,B} < F^*_{IP,B}$
$F^{Total}_{OP,B} < F^*_{OP,B}$
$F^{Total}_{IP,C} < F^*_{IP,C}$
$F^{Total}_{OP,C} < F^*_{OP,C}$
NO
YES
END

CLOSING REMARKS

- Rational (and relatively easy) modelling-aided design methodology is feasible
- Non-negligible experimental characterisation testing effort is implied to obtain test-informed modelling
- Component testing could also call for full-scale façade system testing
- Key steps towards implementation/development of an EAD

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FOR YOUR SAFETY.

THANKS