TURKISH CONSTRUCTIONAL STEELWORK ASSOCIATION (TUCSA)
COLD FORMED STEEL STRUCTURES WORKSHOP
Istanbul 25 March 2013

Lightweight Steel Framing Houses in Seismic Areas

Behaviour features and needs for Design Technical Regulations

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COLD-FORMED STEEL IN RESIDENTIAL BUILDING

WHY STEEL FRAMED HOUSES?

Because:

- **This is a complete sustainable technology – steel structures are 100% recyclable (*It takes 6 old cars to produce enough steel for the structure of house*);**
- **It enables the use of high performance thermo-energetic materials for cladding and finishing;**
- **It is a highly productive and qualitative technology both for fabrication and erection;**
- **It enables to obtain flexible partitions;**
- **It enables for further up-grade, modifications and/or development.**

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

WHY STEEL FRAMED HOUSES IN SEISMIC AREAS?

Because:

- Excellent structural performance;
- Appropriate to apply Performance Base Design and enables for safe prediction of behavior under severe actions;
- Good robustness, easy to prevent by design the progressive collapse;
- In case, easy to repair;
- Because their high strength/weight ratios and good redundancy, there are the safest houses, provided it is well designed and executed

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

STEEL FRAMED HOUSES:
CLASSICAL OR MODERN APPEARANCE

Cold-formed steel used in:

- Basement walls;
- Floor joists;
- Load bearing walls;
- Non-load bearing walls;
- Roof framing and trusses.

Construction types:

- Stick build;
- Panelized;
- Modular;
- Combination of above.

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

- ***Classical Appearance***

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

- ***Classical Appearence***

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

- ***Classical Appearence***

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

- ***CASSETTE WALL STRUCTURE***

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

- ***CASSETTE WALL STRUCTURE***

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

- ***Wall Stud Structure***

COLD-FORMED STEEL IN RESIDENTIAL BUILDING

- ***Wall Stud Structure***

INTRODUCTION TO SEISMIC DESIGN PRINCIPLES

DESIGN PHILOSOPHY:

- **Dissipative behaviour;**
- **Non- or low- dissipative behaviour.**

Design Criteria

- Ultimate limit state (collapse prevention)
- Damageability limit state (progressive design criteria in order to limit damage)
- Serviceability limit state

INTRODUCTION TO SEISMIC DESIGN PRINCIPLES

Dissipative structures

- Energy dissipation taking advantage of the post-elastic load bearing capacity of the structure;
- Design codes: earthquake load reduction through “q” factor.

INTRODUCTION TO SEISMIC DESIGN PRINCIPLES

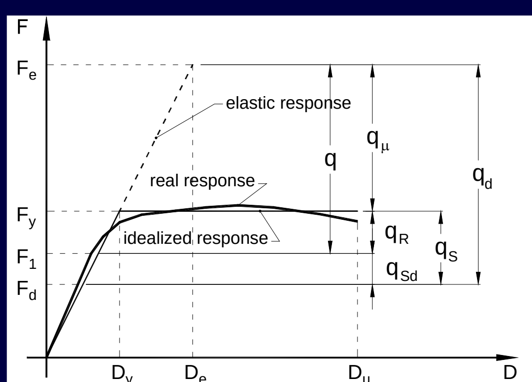
Behavior factor "q" (pr EN 1998-1)

Design concept	Behavior factor "q" EC8	Required ductility class
Highly dissipative structures	$q \geq 4{,}0$	H (high)
Medium dissipative structures	$2{,}0 \leq q < 4{,}0$	M (medium)
Structures with limited dissipation	$q = 1{,}5\text{-}2{,}0$	L (low)

Question: *Thin walled steel structures are low dissipative?*

INTRODUCTION TO SEISMIC DESIGN PRINCIPLES

Definition of the Earthquake Reduction Factor



Ductility

$$q_\mu = \frac{F_e}{F_y}$$

Structural Overstrength

$$q_s = \frac{F_y}{F_d}$$

$$q_s = q_{Sd} \cdot q_R$$

q_{Sd}-design overstrength

q_R -structural overstrength

$$q_R = \frac{\alpha_u}{\alpha_1}$$

Total reduction factor

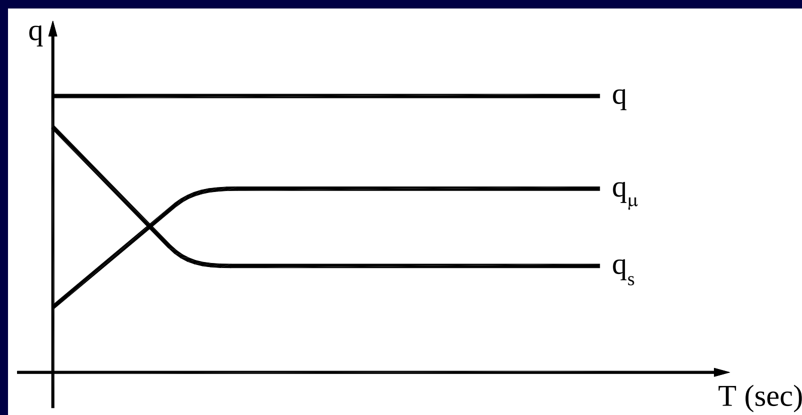
$$q_d = q_\mu \cdot q_s = q_\mu \cdot q_{Sd} \cdot q_R$$

Total reduction factor without overstrength

$$q = q_\mu \cdot q_R$$

INTRODUCTION TO SEISMIC DESIGN PRINCIPLES

Relationships for q, q_{μ}, q_s

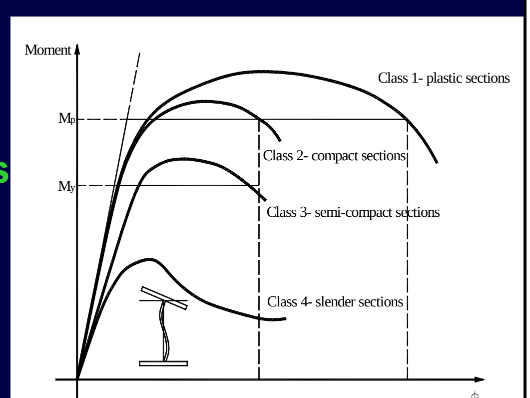


INTRODUCTION TO SEISMIC DESIGN PRINCIPLES

Cold-formed steel framing for housing are usually made of class 4 or 3 sections e.g.

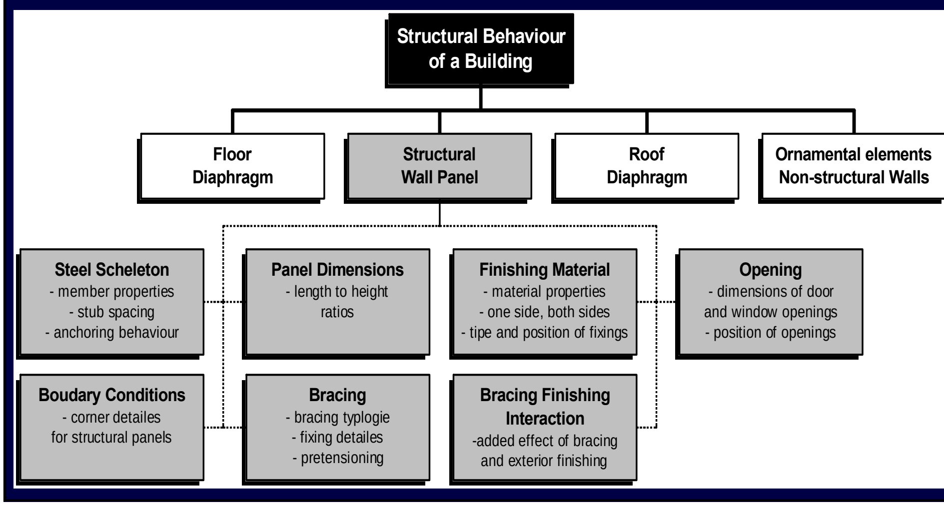
- **Slender sections prone to local buckling;**
- **Non-plastic;**
- **Non-dissipative.**

Seismic design codes are either restrictive or penalizing the use of these structures in seismic zones.



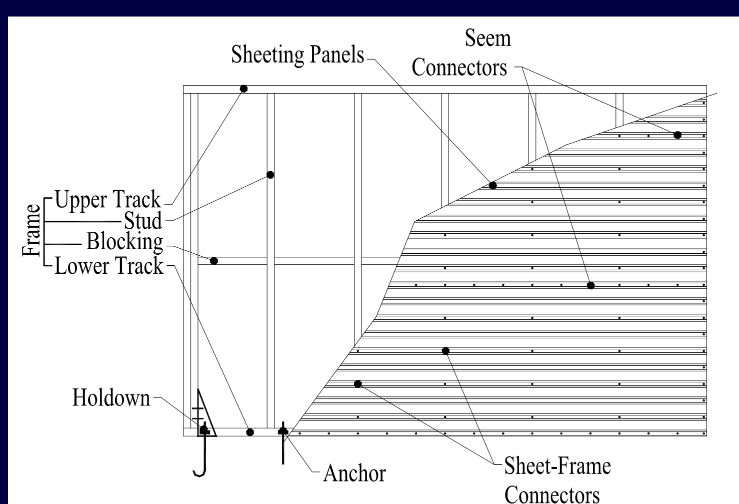
INTRODUCTION TO SEISMIC DESIGN PRINCIPLES

Earthquake behaviour of a house building



INTRODUCTION TO SEISMIC DESIGN PRINCIPLES

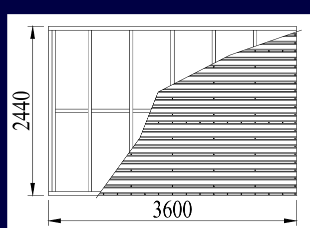
Shear Force Resisting Elements in a Wall Panel



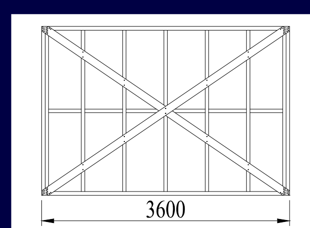
An extensive research program was carried out at the *"Politehnica" University of Timisoara* in order to evaluate and characterize the seismic performance of cold-formed steel framed houses:

- **Tests and numerical simulations on shear panels including connection behavior;**
- **In-situ tests of a house structure in different stages of erection.**

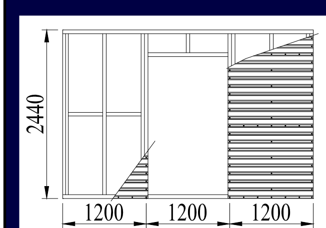
Wall Panel Configurations



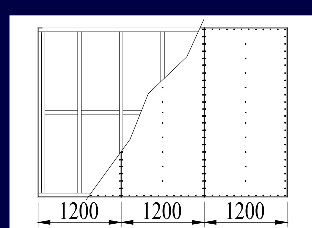
Series I and II



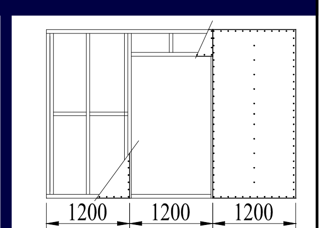
Series III



Series IV



Series OSB-I



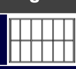
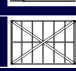
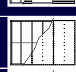
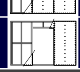
Series OSB-II

TESTING ON WALL PANELS

Wall Panel Typologies

TESTING ON WALL PANELS

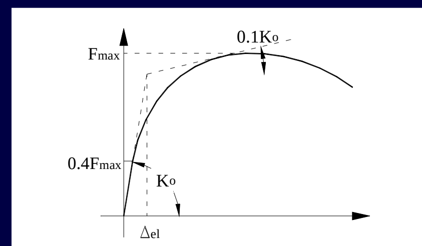
Resistance, Rigidity and Ductility of Load Bearing Wall Panels with Steel Skeleton

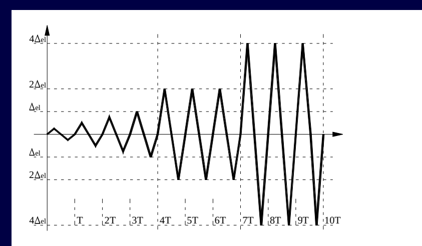
Series	Panel Configuration	Cladding	Testing Method	Load Vel. (cm/min)	No. Test
O		-	Monotonic	1	1
I		Corrugated Sheet LTP20/0.5 (Ext)	Monotonic	1	1
			Cyclic	6	1
			Cyclic	3	1
II		Corrugated Sheet LTP20/0.5 (Ext) Gypsum Board (Int)	Monotonic	1	1
			Cyclic	6	1
			Cyclic	3	1
III		Cross Bracing (Ext-Int)	Monotonic	1	1
			Cyclic	3	1
IV		Corrugated Sheet LTP20/0.5 (Ext)	Monotonic	1	1
			Cyclic	6	1
			Cyclic	3	1
OSB I		10 mm OSB Panels (Ext)	Monotonic	1	1
			Cyclic	3	1
OSB II		10 mm OSB Panels (ext)	Monotonic	1	1
			Cyclic	3	1
Total Number of Specimens					**15**

TESTING ON WALL PANELS

Testing Procedure

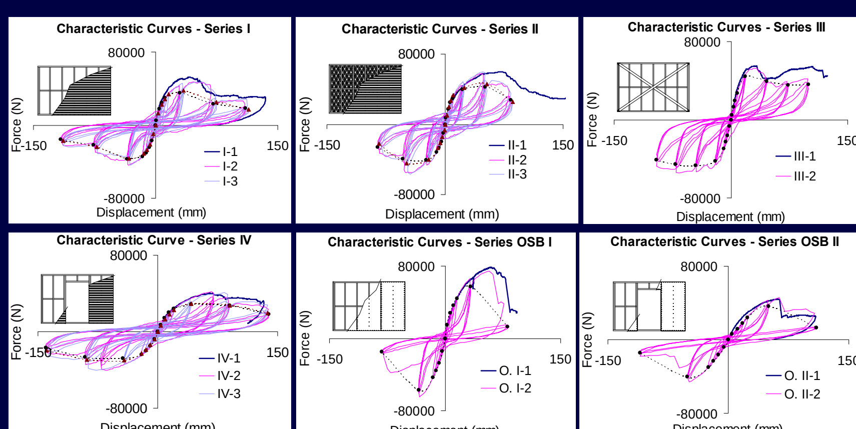
- **Monotonic test, with loading velocity of 1cm/min;**
- **From monotonic curve, determination of the Conventional Elastic Limit Displacement (Δ_{el});**
- **Cyclic testing followed ECCS recommendation, ($\frac{1}{4}\Delta_{el}$, $\frac{1}{2}\Delta_{el}$, $\frac{3}{4}\Delta_{el}$, $1\Delta_{el}$, 3x $2\Delta_{el}$, 3x $4\Delta_{el}$, 3x $6\Delta_{el}$,…), until significant decrease of capacity.**





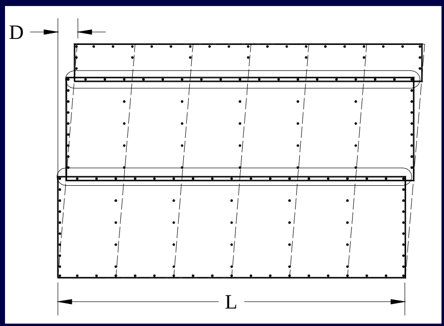
TESTING ON WALL PANELS

Experimental Load-Displacement Curves

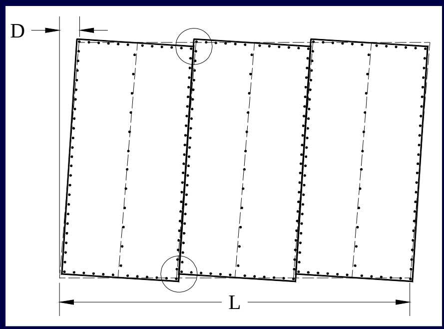


TESTING ON WALL PANELS

Failure Modes



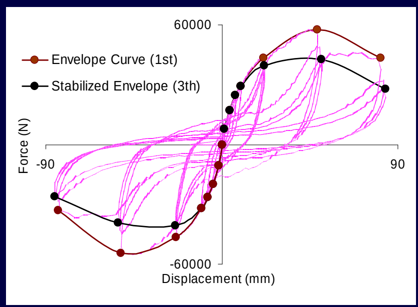
Steel sheeting to steel framing



OSB panels to steel framing

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Testing: Characteristics of the Cyclic Behaviour

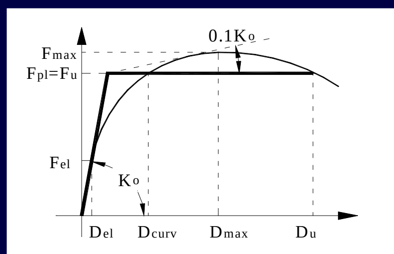


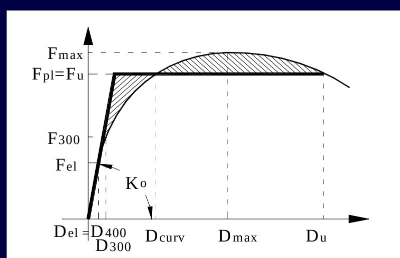
- Characteristics of the hysteretic behaviour:
  - Nonlinearity;
  - Strong pinching;
  - Low Strength and Stiffness degradation;
  - Performance controlled by connection.

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Testing: Equivalent models

Method I - Method II

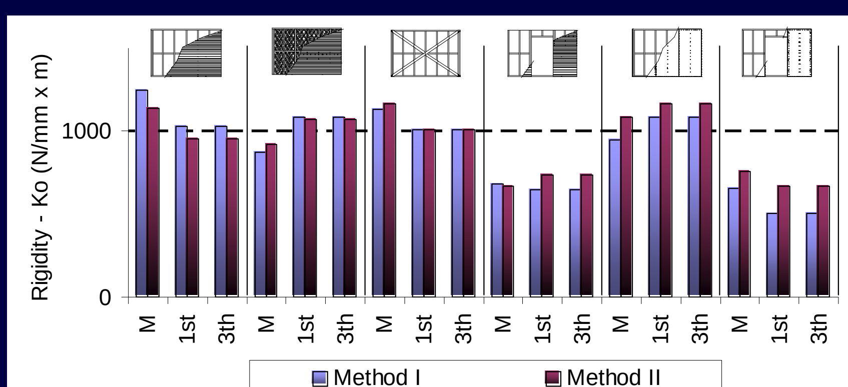




- K_o up to the value of F_{el} ($0.4F_{max}$);
- $0.1K_o$ rigidity tangent to the experimental curve;
- F_u at intersection;
- D_u at intersection with the downloading branch;
- D_{400} corresponding to 1/400 rad panel top rotation;
- Initial stiffness (K_o), stiffness up to F_{el} (D_{400});
- F_u so as shaded areas are equal;
- D_u at intersection with the downloading branch;

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

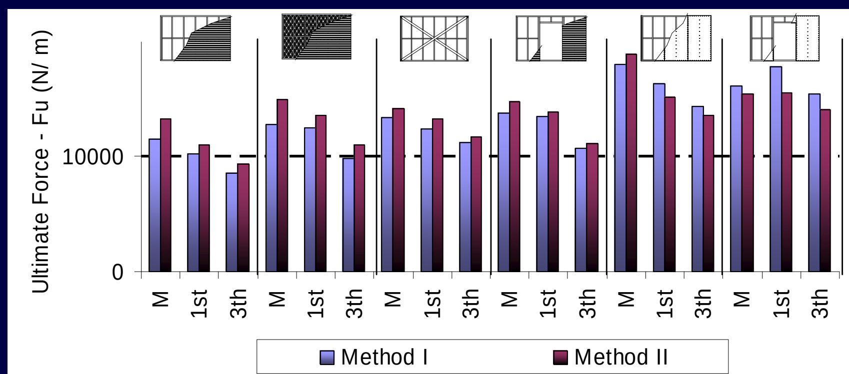
Testing: Initial Rigidity (K_o)



- **Because of Lintel , rigidity underevaluated for specimens with openings;**

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

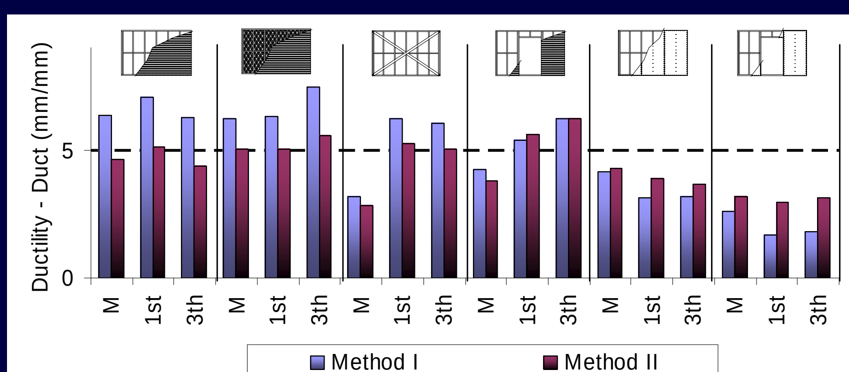
Testing: Ultimate Force (F_u)



- **Strength degradation for all specimens;**
- **Higher values for OSB specimens;**

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

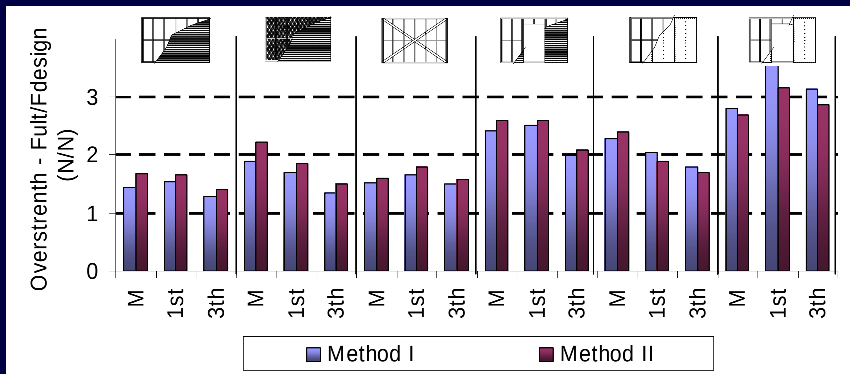
Testing: Ductility ($D_{uct} = D_u/D_y$)



- **Unexpected corner failure for specimen III-1;**
- **Lower ductility provided by OSB specimens;**

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Testing: Overstrength (F_u/F_{design})

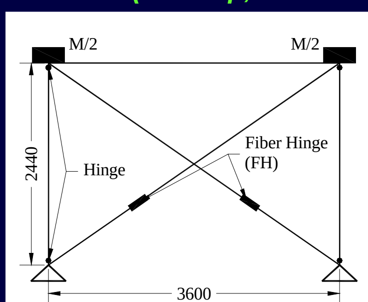


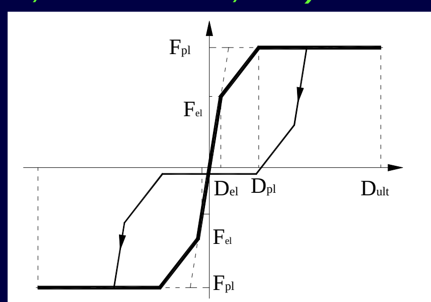
- F_{design} at minimum of $2/3F_u$ and F_{300} (1/300 rad);
- Overstrength in the range of 1.2-1.6;
- Values less relevant for panels with openings;

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Numerical: Proposed Model

(L. Fulop, PhD Thesis, P.U. Timisoara, 2003)

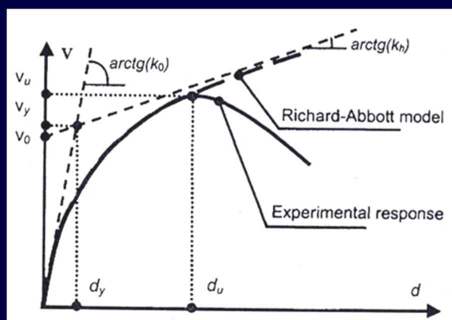




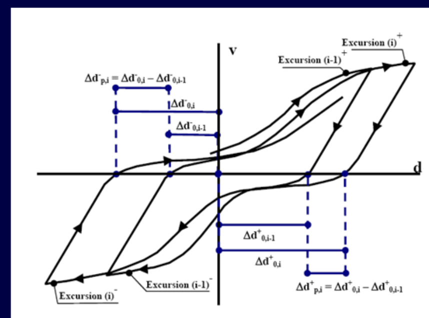
- The panel is replaced by an equivalent brace system with similar hysteric behavior (DRAIN-3DX);
- Capabilities of the model:
  - Pinching;
  - Non-linearity;
  - NO strength degradation.

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

NONLINEAR MODEL



(Richard-Abbott model parameters)

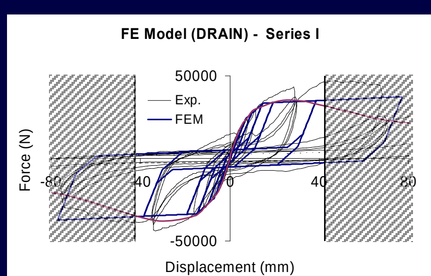


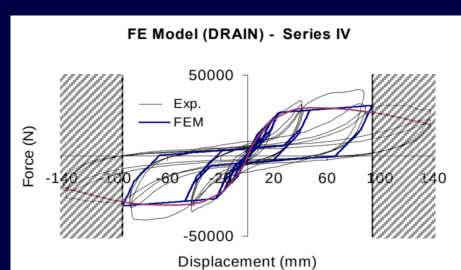
(University of Naples, R. Landolfo et al.)

$$v = \frac{(k_0 - k_h)d}{\left[1 + \left|\frac{(k_0 - k_h)d}{v_0}\right|^n\right]^{1/n}} + k_h d$$

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Numerical: Comparison of Experimental to FE Curve

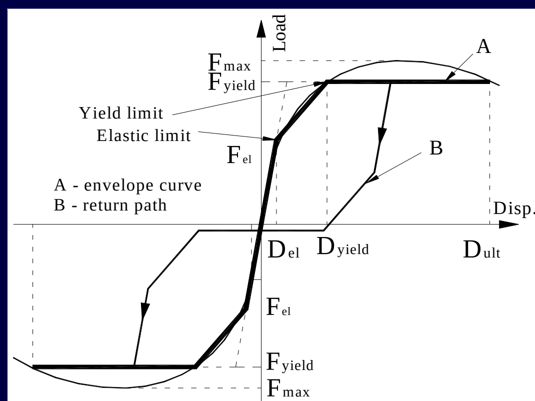


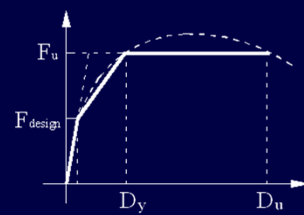


- Capacity limit of the Fulop's FE model has been considered based on stabilized envelope curves;
- If few plastic are considered it can be a simple and safe approach to consider strength degradation;

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Numerical: Interpretation of Limit States



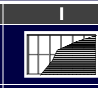
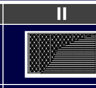
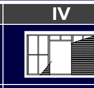
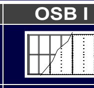
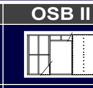


$$D_{uct} = \frac{D_u}{D_y}$$

$$O_{strength} = \frac{F_u}{F_{design}}$$

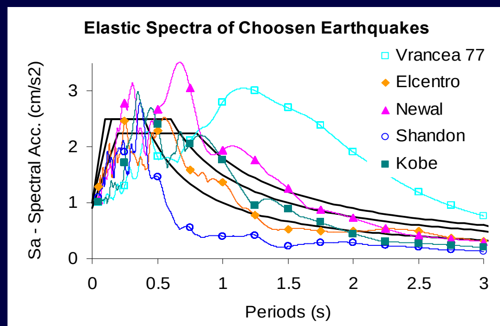
CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Numerical: Panel Characteristics for the Analysis

Series	I	II	IV	OSB I	OSB II
Wall Panel Scheme					
Initial Rigidity (N/mm)	3446.6	3850.6	1766.3	4197.3	1610.5
Elastic Limit (F_{el}) (N)	24086	26566	128670	28942	11850
Yield Limit (F_{yield}) (N)	33560	39819	26812	48944	33908
Yield Limit (D_{yield}) (mm)	*14.95*	*15.58*	*23.78*	*17.49*	*27.76*
Ultimate Limit (D_{ult}) (mm)	42.61	57.29	94.35	42.85	65.57
Duct	*4.37*	*5.54*	*6.22*	*3.67*	*3.11*

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

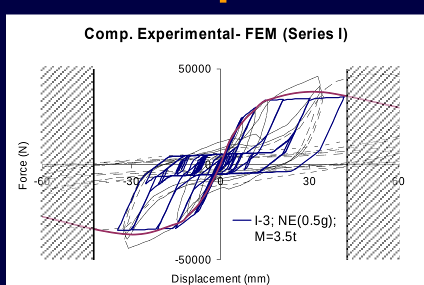
Numerical: Spectra of EQ Records for Time History Analysis

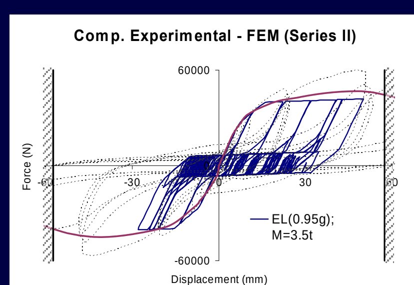


- Time history analysis using the SDOF FE models;
- Masses of 2, 2.5, 3, 3.5 and 4 t;
- Records scaled from 0.05g to 2g (IDA);

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Numerical: Examples of Dynamic Response at Ultimate State

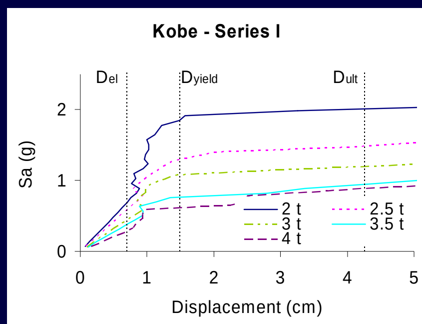


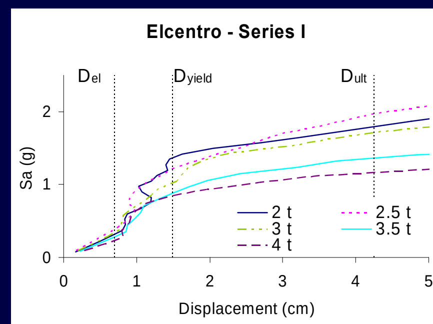


- Main characteristics of the hysteretic behavior are covered;
- Few plastic excursions in ultimate state (3-5);
- The approach with the stabilized envelope curves seems to be safe and reasonable;

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Numerical: Series I - IDA Curves

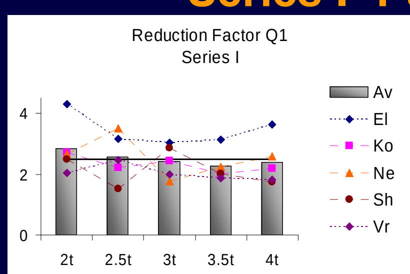


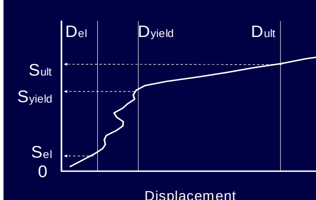


- **Important difference between earthquake level at the elastic and yield limit (*overstrength*);**
- **Less between yield and ultimate (*ductility*);**

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Numerical: Series I -Partial 'q' Values

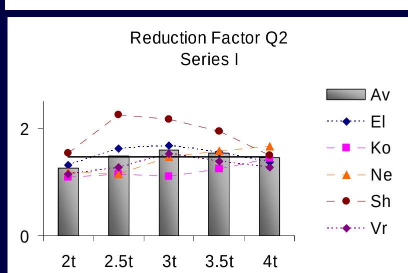


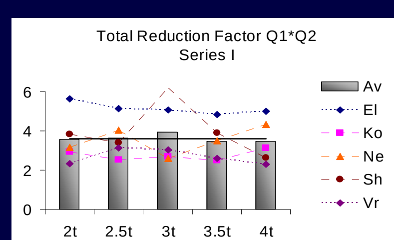


$$q_1 = \frac{S_{yield}}{S_{el}};$$

$$q_2 = \frac{S_{ult}}{S_{yield}};$$

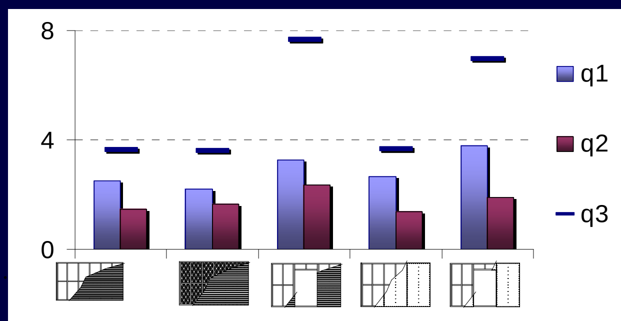
$$q_3 = q_1 \times q_2 = \frac{S_{ult}}{S_{el}};$$

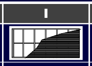
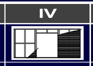
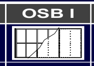
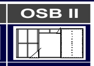




CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Numerical: Summary of ‘q’ Values



Series	I	II	IV	OSB I	OSB II
Scheme					
q1	*2.5*	*2.21*	*3.28*	*2.66*	*3.78*
q2	*1.46*	*1.65*	*2.36*	*1.38*	*1.88*
q3	*3.62*	*3.61*	*7.65*	*3.67*	*6.96*

CALIBRATION OF SIMPLIFIED HYSTERETIC MODEL

Wall Panel Results

q_μ = 1,4 – 1,6

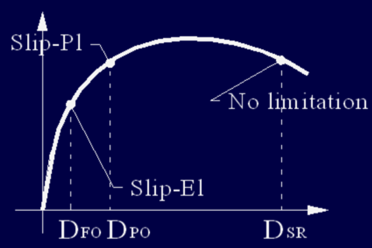
q_s = 2,2 – 2,6

q_d = 3,0 – 4,0

The performance of the wall panels is governed by the performance of seam and sheeting to skeleton fasteners

PERFORMANCE OF CONNECTIONS

Tests: Performance criteria based on fastener slip



FO - Fully Operational: *elastic deformations and small plastic elongation in fastener holes (drift<0.003);*

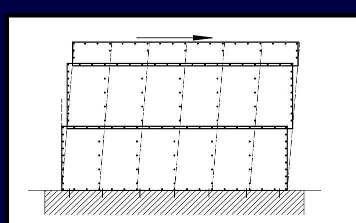
PO - Partially Operational: *local repairs of the sheeting system required against water proofing (drift<0.015);*

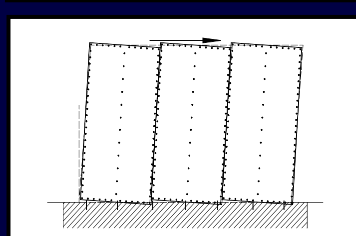
SR - Safe but Repairs required: *replacement of the sheeting is necessary, but the building is safe against collapse (drift<0.025);*

Specimen	Maximum slip in fasteners (mm)	Panel top displacement (mm)	Drift (%)
I-3	0.197	6.71	0.274
	4.8	29.22	1.197
IV-2	0.197	7.96	0.326
	4.8	44.13	1.808
IV-3	0.197	8.11	0.332
	4.8	42.22	1.730

PERFORMANCE OF CONNECTIONS

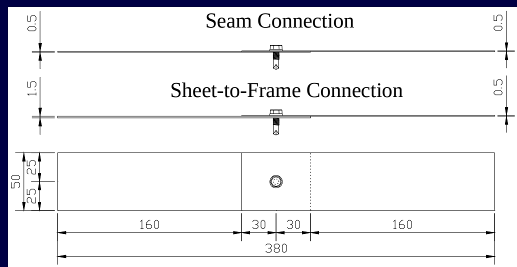
DEFORMATIONS OF WALL-PANELS





PERFORMANCE OF CONNECTIONS

STEEL-TO-STEEL CONNECTIONS

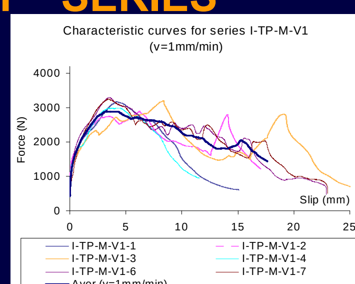


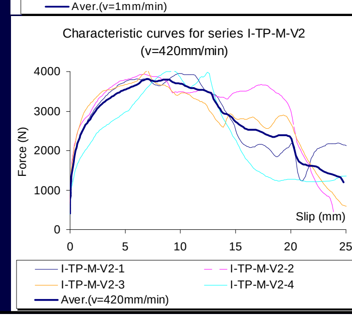
- Representative for connection typologies used in the wall panels, two types of specimens:
  - corrugated sheet to skeleton (0.417 mm to 1.42 mm) using SD3-T15-4.8×22 (4.8 mm) screws (Series I-TP)
  - corrugated sheet to corrugated sheet (0.417 mm to 0.417 mm) using SL2-T-A14-4.8×20 (4.8 mm) screws (Series I-TT)
- Dimensions according to the ECCS P21, facilitate bearing failure of the thinner sheet;
- With the same materials and in similar conditions as the connections in the panels;
- Two loading velocities:
  - V_1=1mm/min for quasi static loading conditions
  - V_2=420mm/min for high velocity tests.

PERFORMANCE OF CONNECTIONS

FAILURE MODES AND CHARACTERISTIC CURVES FOR "I-TP" SERIES

Failure mode for series I-TP-V1

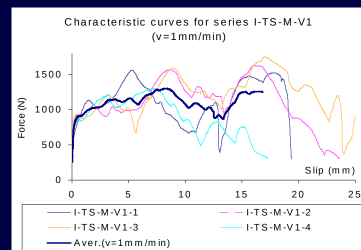




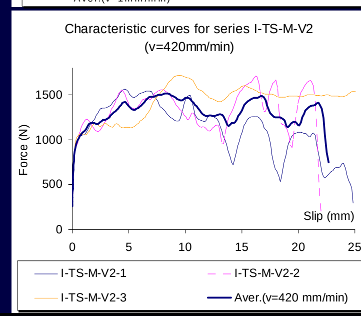
PERFORMANCE OF CONNECTIONS

FAILURE MODES AND CHARACTERISTIC CURVES FOR "I-TT" SERIES

I-TT-V1

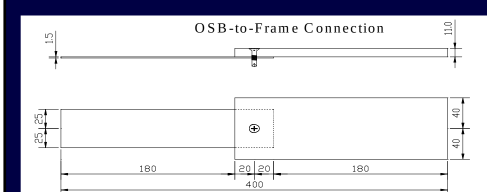


I-TT-V2

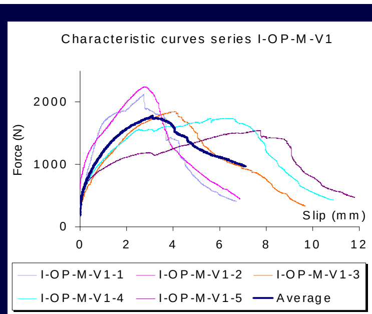


PERFORMANCE OF CONNECTIONS

OSB-TO-STEEL CONNECTIONS

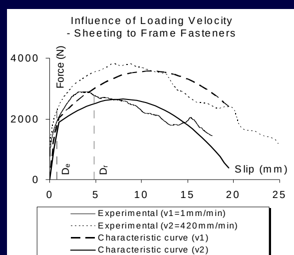


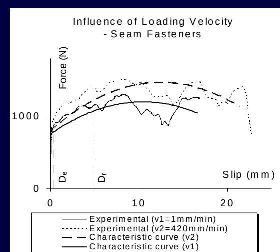
- Very inhomogeneous results;
- No conclusion can be drawn;
- OSB connections possess less ductility.

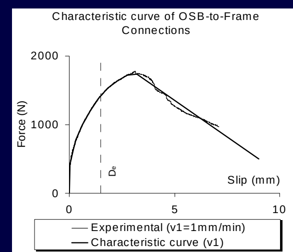


PERFORMANCE OF CONNECTIONS

DESIGN CRITERIA FOR CONNECTIONS



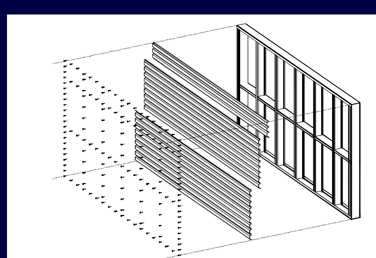


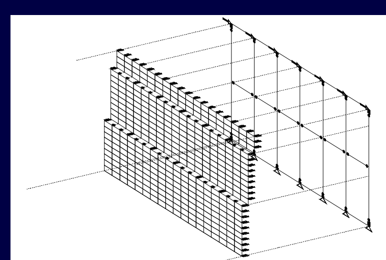


- **Significant ductility of steel-to-steel connections with the possibility to use multi level design criteria;**
- **Important overstrength for steel-to-steel connections;**
- **In case of the OSB-to-steel connections failure is non ductile without possibility to use multi level design criteria;**

PERFORMANCE OF CONNECTIONS

CONSTRUCTING THE *FE* MODEL

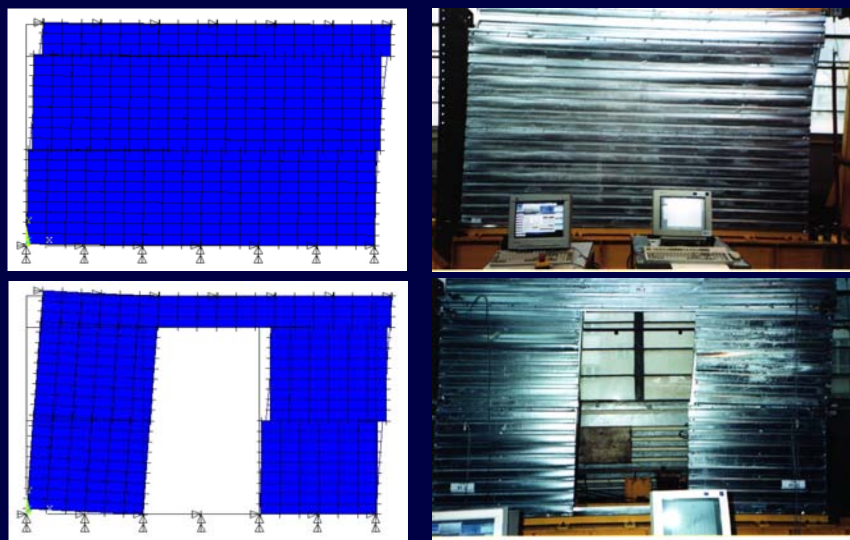




- The FE model takes into account the:
  - Elastic shear deformation characteristics of the corrugated sheeting (including end distortion);
  - Elastic deformation characteristics of the skeleton;
  - Non-linear deformation characteristics of sheeting-to-framing and seam connections;
  - Non-linear characteristics of hold-down details.

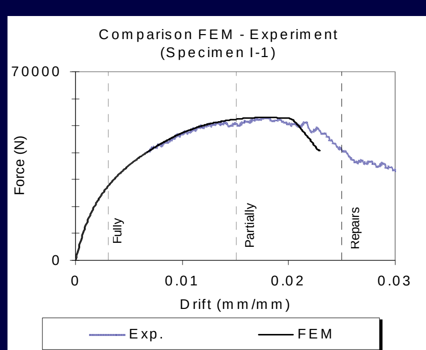
PERFORMANCE OF CONNECTIONS

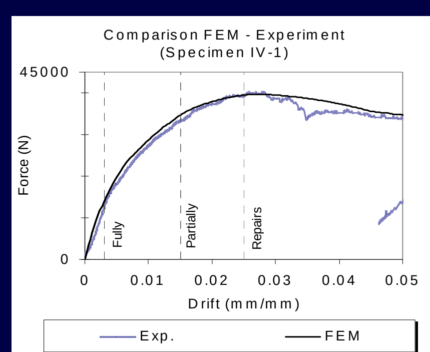
DEFORMATION OF THE *FE* MODEL



PERFORMANCE OF CONNECTIONS

DESIGN CRITERIA TRANSLATED FROM CONNECTION TO WALL-PANEL LEVEL





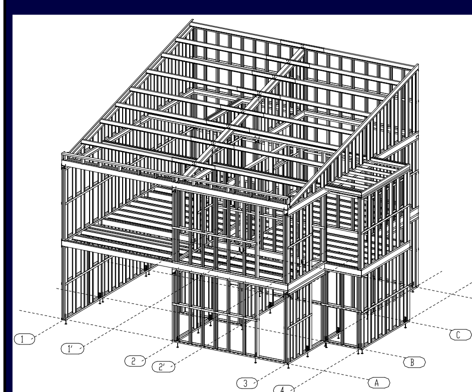
- The design criteria for connections determines the criteria for panels
- Because low degradation of strength and stiffness in cyclic , monotonic analysis might apply

IN-SITU MEASUREMENTS

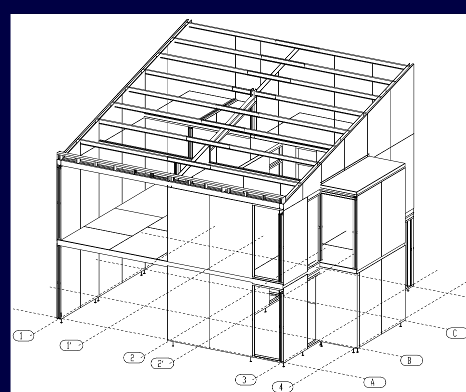
In-situ tests of a house structure in different stages of erection

IN-SITU MEASUREMENTS

Structural design based on tested panels



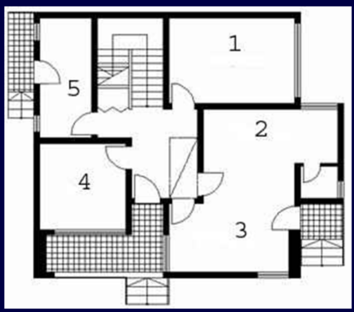
Steel skeleton of the structure

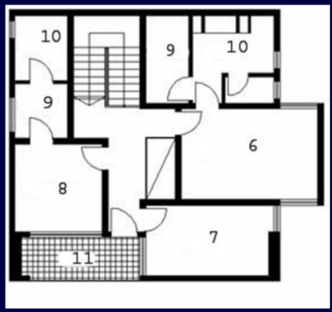


The skeleton with the structural OSB sheeting

IN-SITU MEASUREMENTS

Story Plans





IN-SITU MEASUREMENTS

Design assisted by testing

$$E_{s,i} < R_{s,i}$$

$$R_{s,i} = R_k \cdot L_i$$

where,

$E_{s,i}$ = total shear force induced by seismic action on "i" direction (kN);

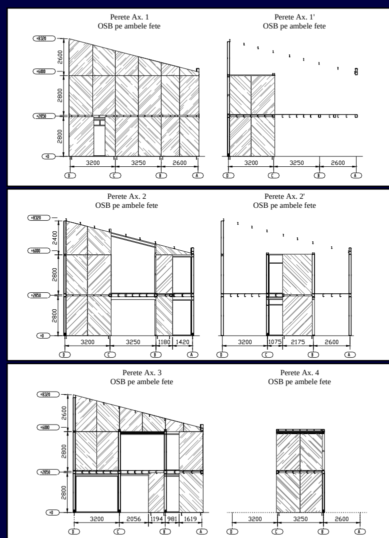
$R_{s,i}$ = total shear wall resistance on "i" direction (kN);

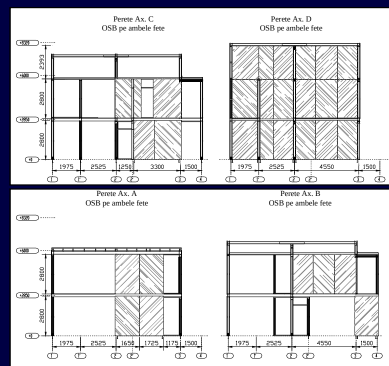
R_k = characteristic strength of shear wall (kN/m);

L_i = length of shear wall on "i" direction (m).

IN-SITU MEASUREMENTS

Design assisted by testing





Transversal:

L_{gf} =21.55 m, L_{ff} =17.12 m

Longitudinal:

L_{gf} =17.22 m, L_{ff} =12.42 m

IN-SITU MEASUREMENTS

Three subsequent erection stages

- **Steel framing only;**
- **Steel framing with OSB panels;**
- **Steel framing with finishing.**

Modal dynamic characteristic compared :

Numerical vs. measures

IN-SITU MEASUREMENTS

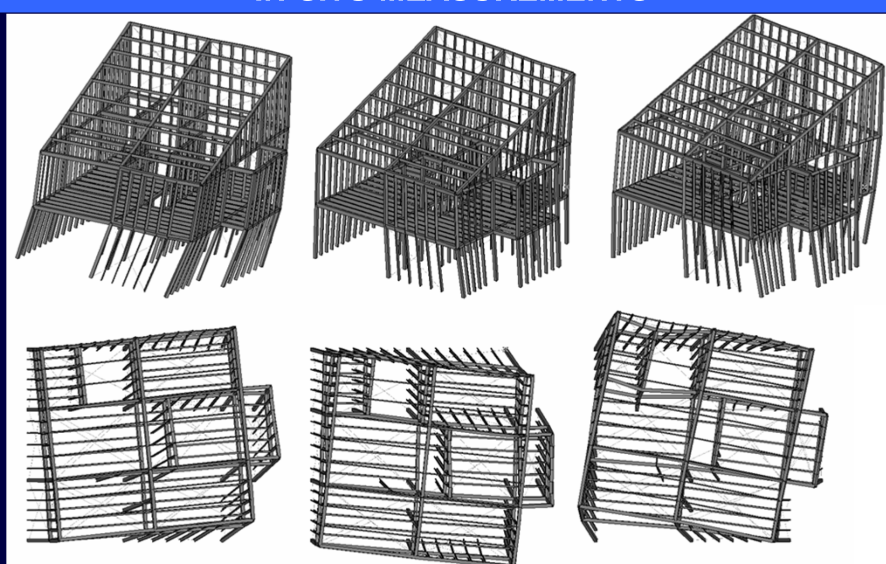
Modal parameters obtained by FE modeling

Stage	T_1 (s)	Type*	T_2 (s)	Type*	T_3 (s)	Type*
1	0.44	Tr	0.39	To	0.35	Lo
2	0.19	Lo	0.18	Tr	0.13	To
3**	0.33	Lo	0.31	Tr	0.23	To

* Note[1]: Tr – transversal, Lo – longitudinal, To - Torsional

** Note[2]: Only the masses changed from Stage 2 to Stage 3

IN-SITU MEASUREMENTS



(a) (b) (c)

Mode shapes in Stage 2 (FE modeling):

(a) first mode - T_1, (b) second mode - T_2, (c) third mode - T_3

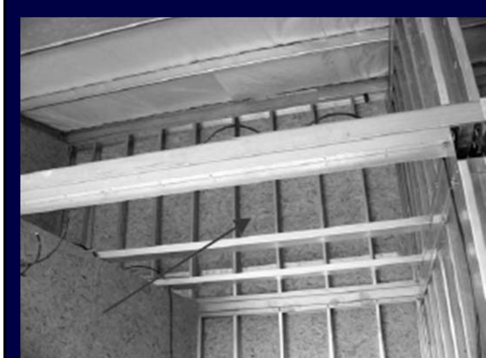
IN-SITU MEASUREMENTS

In-situ measurements (1)

Construction Stage 1 and measurement sensor location on the skeleton of the structure

IN-SITU MEASUREMENTS

In-situ measurements (2)



Construction Stage 2 and measurement sensor location

IN-SITU MEASUREMENTS

In-situ measurements (3)

Construction Stage 3 and measurement sensor location

IN-SITU MEASUREMENTS

Modal parameters based on the analysis of ambient vibrations (in different stages "S")

S	Mode 1			Mode 2			Mode 3		
	T_1 (s)	ξ_1 (%)	Type	T_2 (s)	ξ_2 (%)	Type	T_3 (s)	ξ_3 (%)	Type
1	.546	1.2	Lo	.437	1.1	Tr	.456	1.3	To
2	.103	3.4	Tr	.096	3.7	Lo	-	-	-
3	.101	4.1	Tr	.096	3.8	Lo	.072	4.1	To

* Note: Vibration shapes: Tr – transversal, Lo – longitudinal, To - Torsional

Conclusions

- **Very good 2D behaviour of the wall:**
  - **Robust , e.g. high redundancy;**
  - **Moderate ductility available ;**
  - **Performance dominated by connection behaviour.**
- **Structural design based on calibrated panels, e.g. stiffness vs. capacity, confirmed**
- **Significant contribution of finishing**
- **Damping ratio of 5% confirmed.**

Conclusions :Design Recommendations

- Cold formed steel framed houses will designed as ***low dissipative*** structures
- **q= 1.5-2.0**, and general rules for conceptual seismic design – EN 1998-1: regularity, continuity of axes, low stiffness and mass eccentricity , ductile connecting technology
- Elastic design of steel framing according to **EN 1993-1.1, EN 1993-1-3, EN 1993-1-8**
- ***Standard detailing***
- ***Prescriptive method* design** : pre-calibrated wall-stud panel units , numerical or tests for all-steel solutions, tests for composite; calibrated models for connections allways .
- ***Lightweight flooring*** – dry or light concrete; ***Lightweight envelope***; ***diaphragm capacity*** available enabling for *box-type* behaviour of the building
- Proper foundation design