European Commission

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STEEL-EARTH

STEEL-BASED APPLICATIONS IN EARTHQUAKE-PRONE AREAS

PRECASTEEL

PREFABRI**CA**TED **ST**EEL STRUCTUR**E**S FOR LOW-RIS**E** BUI**L**DINGS IN SEISMIC AREAS

WORKING EXAMPLES

FERRIERE NORD SpA CONTRIBUTION

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TABLE OF CONTENTS

1. Introduction 2
2. Case study n°1 (dissipative r.c. walls)... 2
3. Case study n°2 (dissipative r.c. walls)... 6
4. Case study n°1 (dissipative devices + elastic r.c. walls) 8
5. Case study n°3 (comparison between *FeNO* r.c. wall bracing system and *UniCAM* steel bracing system) 10

1. Introduction

The following paragraphs describe Ferriere Nord SpA (FeNO) contribution on *Precasteel* research in terms of application the pre-design procedure explained in detail through the document “STEEL-EARTH project - WP1 - Technical sheet” to specific study cases.

Here after is reported a summary of the main characteristics of the two selected Commercial Buildings, with the main pre-design results about precast double-slab r.c. wall as alternative bracing system.

2. Case study n°1 (dissipative r.c. walls)

This is a two-storey Commercial Building, covering an area for each floor (see Figure 1) of:

A_{CBs} = D x L = 36 x 50 = 1800 m^2

First of all, the intensity of live loads applied to CBs structures are:

Q_{k1} = 5 kN/m^2 (standard live load, on the first floor)

Q_{k2} = 2 kN/m^2 (snow live load, on the second floor)

The site seismicity level (PGA, peak ground acceleration) is:

a_g = 0.32 g (high seismicity area)

The distribution of the storey forces, with reference to the numbers of the stories and the nature of actions (seismic), is type “C”.

Ductility class of the structure assumed is “DCH” for dissipative structures under cyclic loads generated by an earthquake.

A correct estimation of behaviour factor “q” of the structure depends on ductility class and geometrical properties of the r.c. wall (storey height, width, thickness):

H = 5.00 m (interstorey height)

B = 6.00 m (width of the r.c. wall)

s = 0.25 m (thickness of the r.c. wall)

then, according to *Eurocode 8* provisions, the behaviour factor is assumed:

q = 3.56 (behaviour factor)

Refining the range database about shear horizontal loads (earthquake, wind) every 250 kN, the best fitting of a dissipative r.c. wall system is reached for:

V_b = 1250 kN (base shear for a single r.c. wall)

that is related to a wall influence area of:

A_{wall} = 444 m^2

Finally, the number of r.c. dissipative walls for each floor and direction (X, Y) is:

$n_{wall} = A_{CBs} / A_{wall} = 1800 / 444 \approx 4$

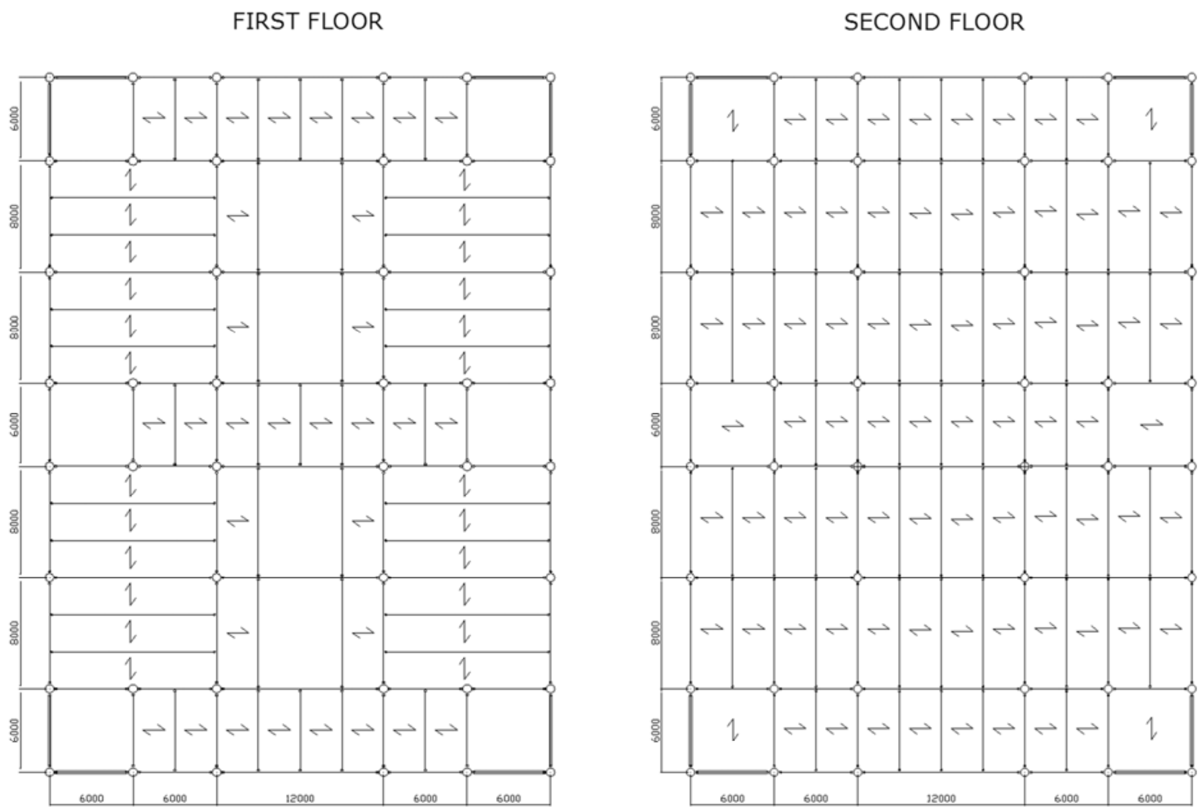

Figure 1: Case study n°1 (dissipative r.c. walls).

Here are reported briefly, according to *Eurocode 2* and *Eurocode 8* suggestions and provisions, all the main structural design and verifications (ULS) about r.c. wall systems.

Material properties:

concrete C30/37 (R_{ck}=37 MPa; f_{ck}=30 MPa; f_{cd}=15.94 MPa)

steel B450C (f_{yk}=450 MPa; f_{tk}=540 MPa; f_{yd}=391 MPa)

Geometrical properties:

s = 0.25 m (r.c. wall resistant thickness)

B = 6.00 m (width of the wall)

H = 5.00 m (interstorey height of the walls)

Actions and verifications (ULS) on r.c. wall system:

Bending moment → $M_{Ed} = (0.38\cdot 1250)\cdot 5.00 + (0.62\cdot 1250)\cdot 10.00 = 10125$ kNm $\leq M_{Rd} = 11524$ kNm

Shear force → $V_{Ed} = 1.5\cdot V_b = 1875$ kN $\leq V_{Rd} = \min(V_{Rsd}, V_{Rcd}) = 1889$ kN

The above ULS verifications are referred to the detailed reinforcing bars and stirrups related to the following technical drawings (see Figure 2), with:

$A_{s,bending}$ = 11+11∅14 (critical region, confined zone $l_c = 0.15\cdot B = 0.90$ m)

$A_{s,shear}$ = 1∅8/10cm

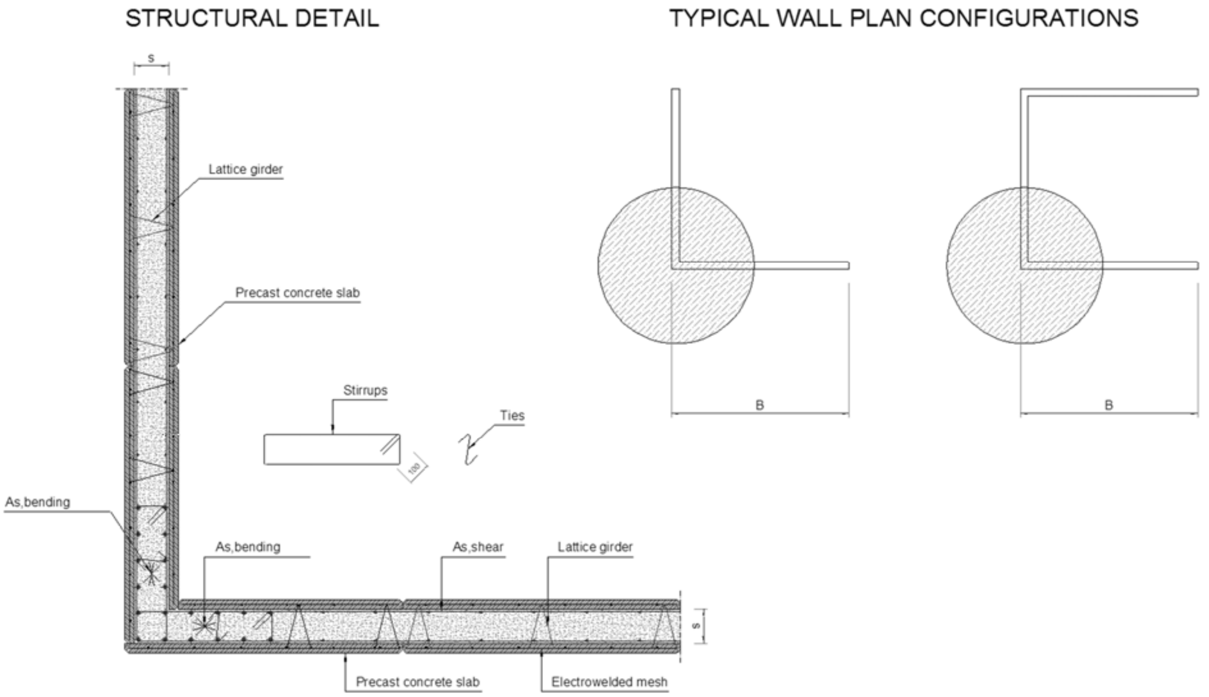

Figure 2: Typical corner structural detail for r.c. wall bracing system and common plan configurations (top view).

Also, the following images describes typical structural details for r.c. shear wall system about:

- structural detail for connection between r.c. wall and r.c. precast floor (see Figure 3);
- structural detail for connection between r.c. wall and its foundation (see Figure 4).

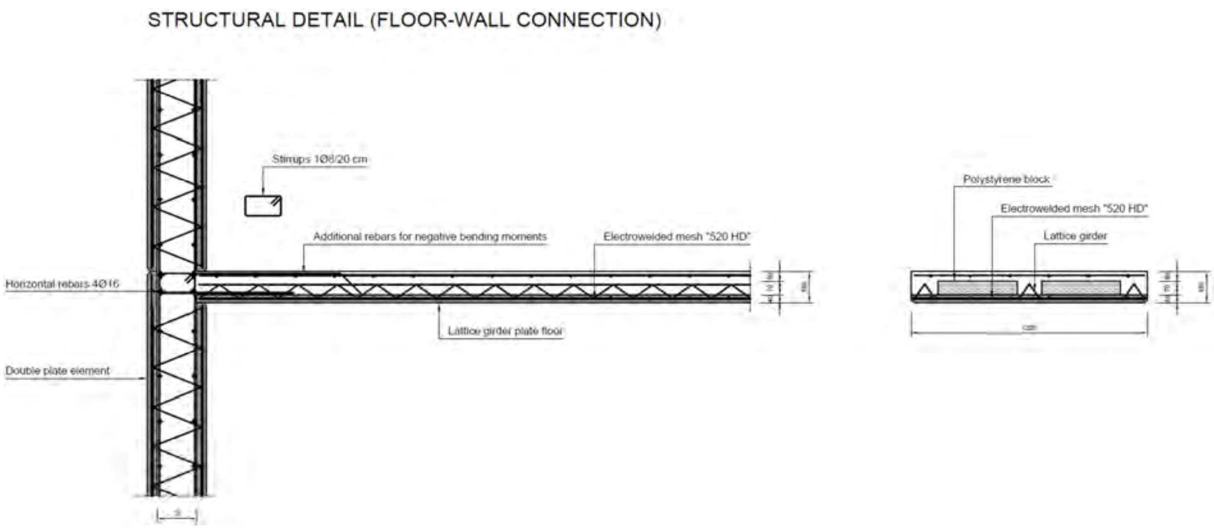

Figure 3: Typical structural detail for connection between r.c. wall and r.c. precast floor (vertical section).

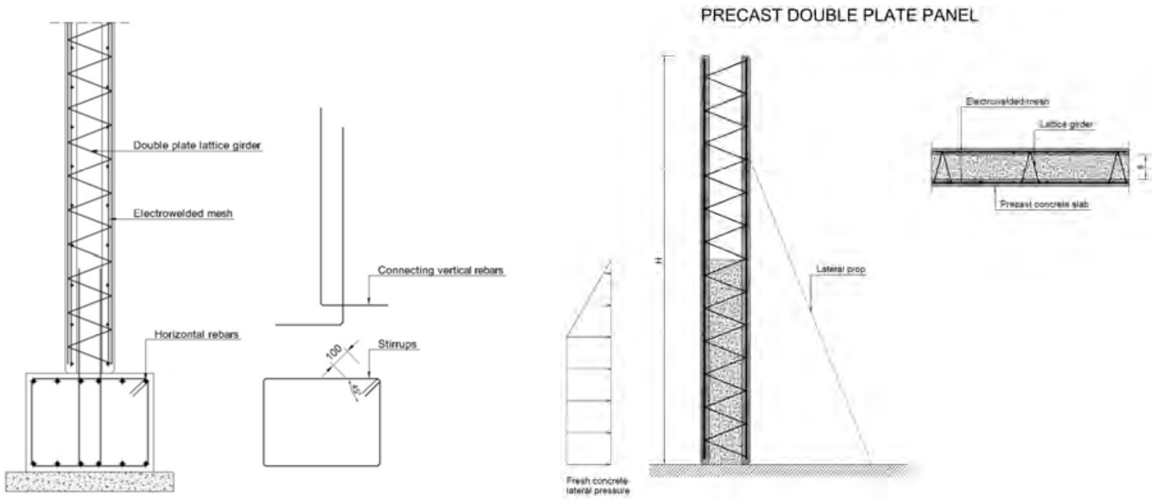

Figure 4: Typical structural detail for connection between r.c. wall and its foundation (vertical section).

For what concerns structural details about connections between the main steel structure (beams, columns) and r.c. walls, there are two possible ways of detailing:

<u>Connection decoupling horizontal and vertical loads</u>

In this case we need an additional auxiliary beam, that transfers gravity loads towards the main steel columns, so that we can connect our r.c. bracing system to the steel frame decoupling vertical and horizontal loads (see Figure 5).

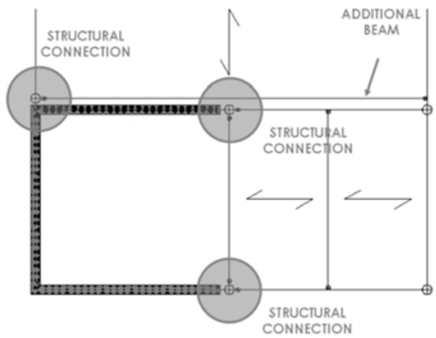

Figure 5: Typical connection between steel structure and r.c. walls, decoupling horizontal and vertical loads (top view).

<u>Connection for both horizontal and vertical loads</u>

In this case we don't need an additional auxiliary beam and we can connect directly our r.c. bracing system to the steel frame; then, it is possible for the walls support even vertical loads without compromise their seismic behaviour (see Figure 6).

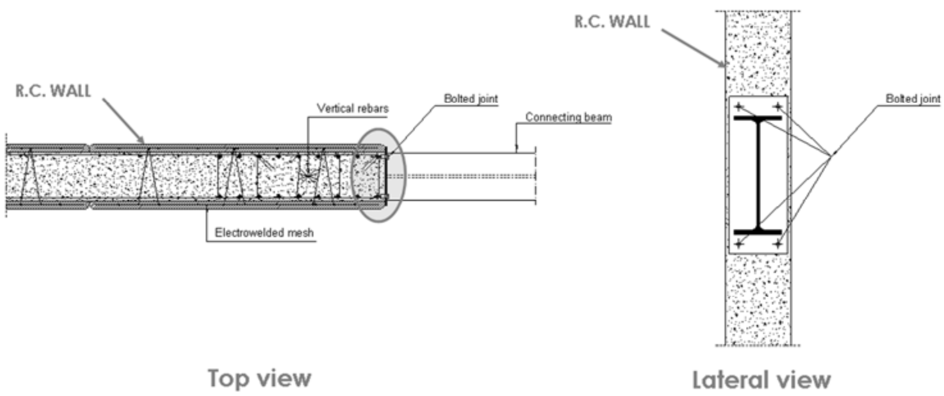

Figure 6: Typical connection between steel structure and r.c. walls for both horizontal and vertical loads.

Connections between steel structure (beams, columns) and r.c. walls as bracing systems could be realized in an easy way by chemical or mechanical anchors, after the erection of the r.c. structure. Another way to realize this kind of joints is the classical bolted connection, shaped and included in the formwork before the concrete pour. If the main structure is isolated by dissipative devices, at each floor there are specific steel joints to prevent hammering between wall systems and floor structures.

3. Case study n°2 (dissipative r.c. walls)

This is a two-storey Commercial Building, covering an area for each floor (see Figure 7) of:

A_{CBs} = D x L = 36 x 66 = 2376 m^2

First of all, the intensity of live loads applied to CBs structures are:

Q_{k1} = 5 kN/m^2 (standard live load, on the first floor)

Q_{k2} = 2 kN/m^2 (snow live load, on the second floor)

The site seismicity level (PGA, peak ground acceleration) is:

a_g = 0.32 g (high seismicity area)

The distribution of the storey forces, with reference to the numbers of the stories and the nature of actions (seismic), is type "C".

Ductility class of the structure assumed is "DCH" for dissipative structures under cyclic loads generated by an earthquake.

A correct estimation of behaviour factor "q" of the structure depends on ductility class and geometrical properties of the r.c. wall (storey height, width, thickness):

H = 5.00 m (interstorey height)

B = 6.00 m (width of the r.c. wall)

s = 0.25 m (thickness of the r.c. wall)

then, according to *Eurocode 8* provisions, the behaviour factor is assumed:

q = 3.56 (behaviour factor)

Refining the range database about shear horizontal loads (earthquake, wind) every 250 kN, the best fitting of a dissipative r.c. wall system is reached for:

V_b = 1750 kN (base shear for a single r.c. wall)

that is related to a wall influence area of:

A_{wall} = 618 m^2

Finally, the number of r.c. dissipative walls for each floor and direction (X, Y) is:

$n_{wall} = A_{CBs} / A_{wall}$ = 2376 / 618 ≈ 4

Here are reported briefly, according to *Eurocode 2* and *Eurocode 8* suggestions and provisions, all the main structural design and verifications (ULS) about r.c. wall systems.

Material properties:

concrete C30/37 (R_{ck}=37 MPa; f_{ck}=30 MPa; f_{cd}=15.94 MPa)

steel B450C (f_{yk}=450 MPa; f_{tk}=540 MPa; f_{yd}=391 MPa)

Geometrical properties:

s = 0.25 m (r.c. wall resistant thickness)

B = 6.00 m (width of the wall)

H = 5.00 m (interstorey height of the walls)

Actions and verifications (ULS) on r.c. wall system:

Bending moment → $M_{Ed} = (0.38 \cdot 1750) \cdot 5.00 + (0.62 \cdot 1750) \cdot 10.00 = 14175$ kNm $\leq M_{Rd} = 15384$ kNm

Shear force → $V_{Ed} = 1.5 \cdot V_b = 2625$ kN $\leq V_{Rd} = \min(V_{Rsd}, V_{Rcd}) = 2699$ kN

The above ULS verifications are referred to the detailed reinforcing bars and stirrups related to the previous technical drawing (see Figure 2), with:

$A_{s,bending} = 12+12\varnothing 20$ (critical region, confined zone $l_c = 0.15 \cdot B = 0.90$ m)

$A_{s,shear} = 1\varnothing 10/10$cm

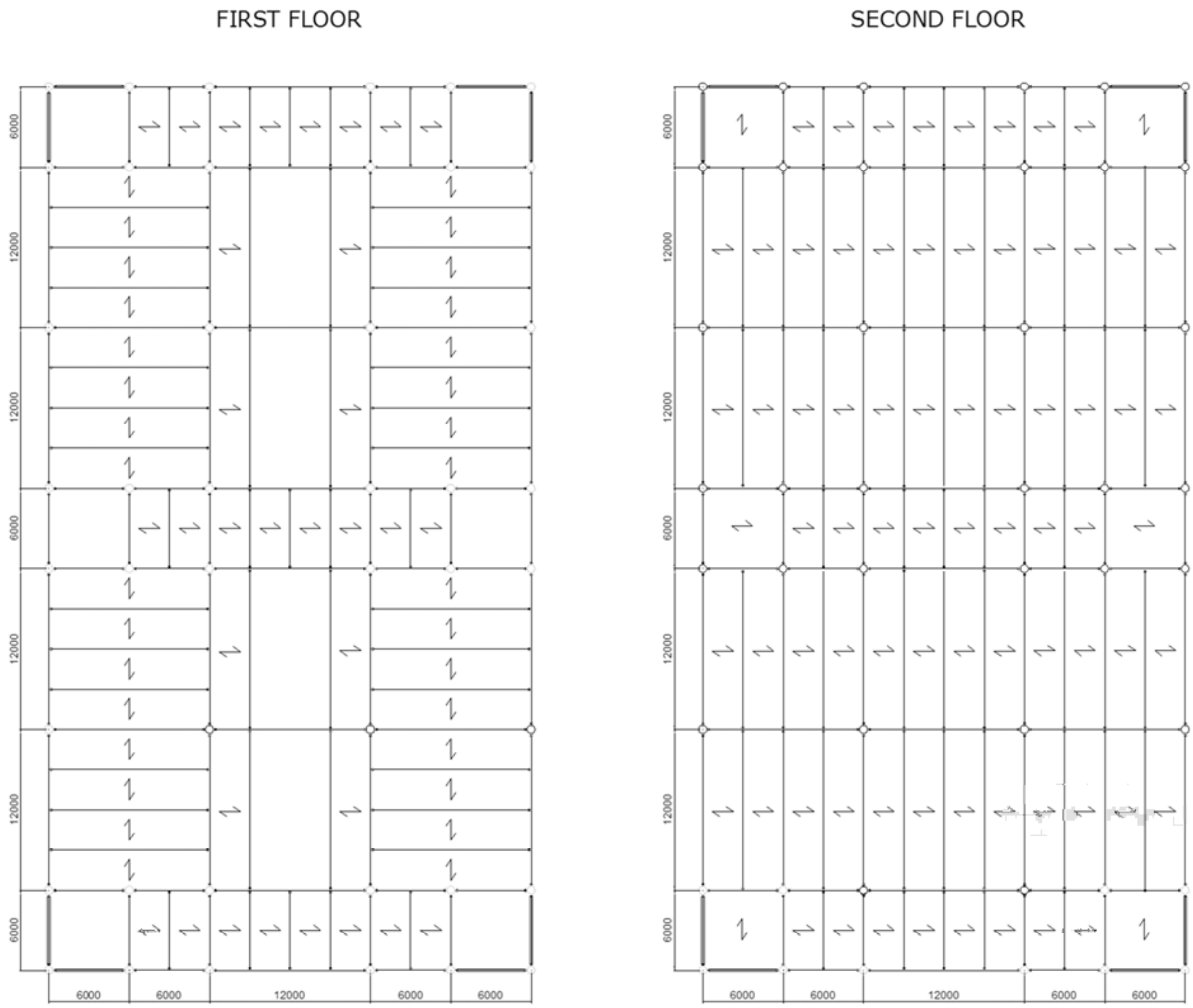

Figure 7: Case study n°2 (dissipative r.c. walls).

4. Case study n°1 (dissipative devices + elastic r.c. walls)

In this paragraph, we examine case study n°1 considering that r.c. walls must maintain an elastic response towards cyclic horizontal actions (seismic) and the largest part of energy due to earthquake has to be dissipated into specific HDR devices (see Figure 8).

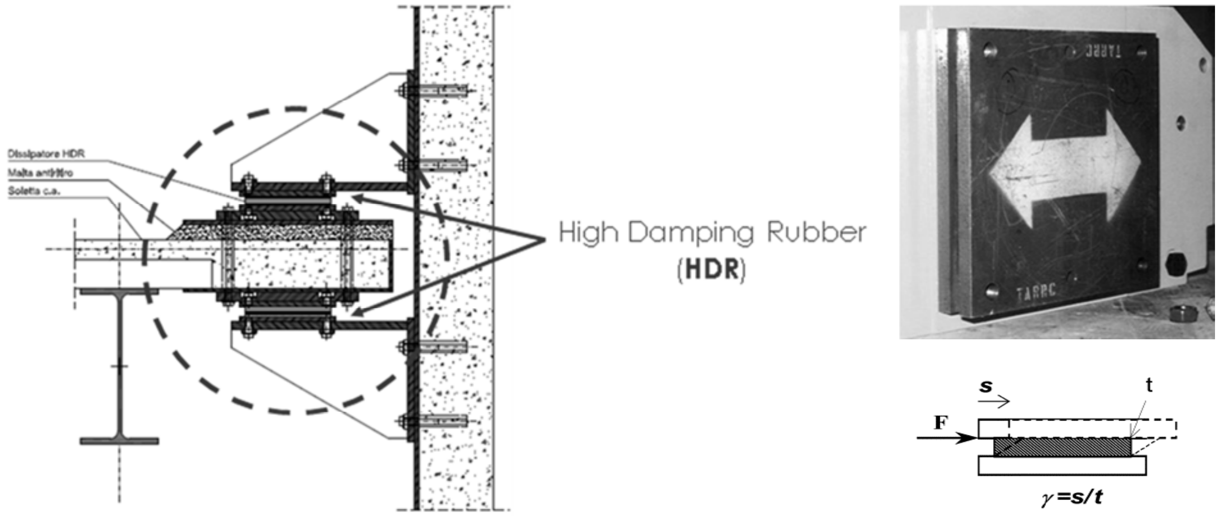

Figure 8: Dissipative device connected to the r.c. wall (High Damping Rubber).

This is a two-storey Commercial Building, covering an area for each floor (see Figure 1) of:

A_{CBs} = D x L = 36 x 50 = 1800 m^2

First of all, the intensity of live loads applied to CBs structures are:

Q_{k1} = 5 kN/m^2 (standard live load, on the first floor)

Q_{k2} = 2 kN/m^2 (snow live load, on the second floor)

The site seismicity level (PGA, peak ground acceleration) is:

a_g = 0.32 g (high seismicity area)

The distribution of the storey forces, with reference to the numbers of the stories and the nature of actions (seismic), is type "C".

Ductility class of the structure assumed is "DCL" for non-dissipative r.c. structures under cyclic loads generated by an earthquake.

Geometrical properties of the r.c. wall (storey height, width, thickness) are:

H = 5.00 m (interstorey height)

B = 4.50 m (width of the r.c. wall)

s = 0.25 m (thickness of the r.c. wall)

The behaviour factor, in this case, is assumed:

q = 1.00 (behaviour factor, elastic structure)

Horizontal forces at the base of each floor and for both directions (X, Y) are:

$F_{X,1}$ = 280 kN

$F_{X,2}$ = 360 kN

$F_{Y,1}$ = 320 kN

$F_{Y,2}$ = 400 kN

In the case of the r.c. wall in direction Y (more stressed than direction X), here are reported briefly, according to *Eurocode 2* suggestions and provisions, all the main structural design and verifications (ULS) about r.c. wall systems.

Material properties:

concrete C30/37 (R_{ck}=37 MPa; f_{ck}=30 MPa; f_{cd}=15.94 MPa)

steel B450C (f_{yk}=450 MPa; f_{tk}=540 MPa; f_{yd}=391 MPa)

Geometrical properties:

s = 0.25 m (r.c. wall resistant thickness)

B = 4.50 m (width of the wall)

H = 5.00 m (interstorey height of the walls)

Actions and verifications (ULS) on r.c. wall system:

Bending moment → M_{Ed} = 320·5.00 + 400·10.00 = 5600 kNm ≤ M_{Rd} = 5770 kNm

Shear force → V_{Ed} = V_b = 320 + 400 = 720 kN ≤ V_{Rd} = min (V_{Rsd}, V_{Rcd}) = 944 kN

The above ULS verifications are referred to the detailed reinforcing bars and stirrups related to the next technical drawing (see Figure 9), with:

$A_{s,bending}$ = 9+9∅16

$A_{s,shear}$ = 1∅8/15cm

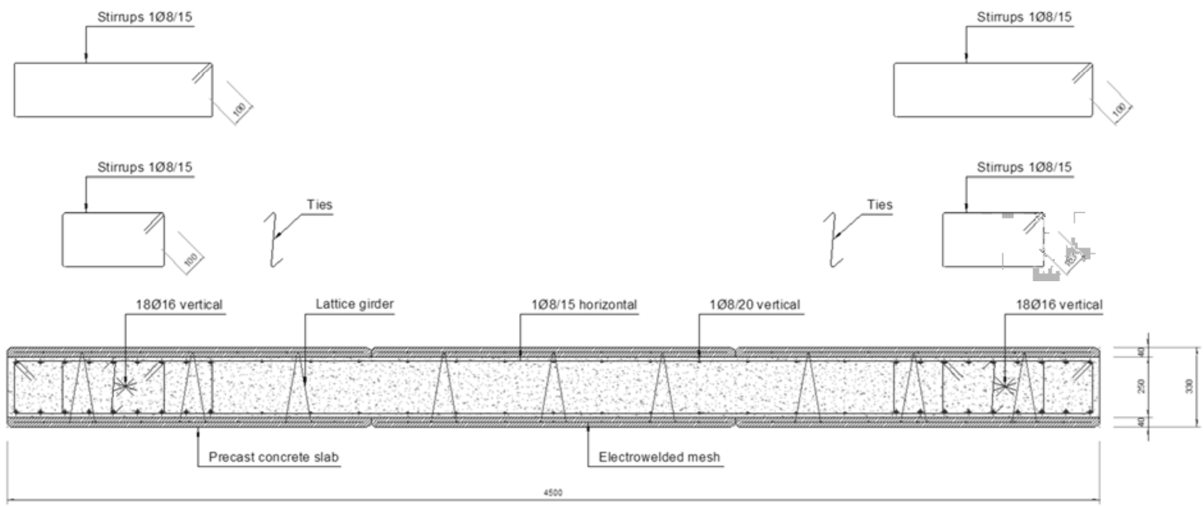

Figure 9: Technical drawing for r.c. wall (study case n°1, dissipative devices coupled with r.c. walls).

5. Case study n°3 (comparison between *FeNO* r.c. wall bracing system and *UniCAM* steel bracing system)

This is a two-storey Commercial Building, also analysed by UniCAM as a *working example* for eccentric steel bracing systems, covering an area for each floor of:

$A_{CBs} = D \times L = 36 \times 66 = 2376\ m^2$

First of all, the intensity of live loads applied to CBs structures are:

$Q_{k1} = 5\ kN/m^2$ (standard live load, on the first floor)

$Q_{k2} = 2\ kN/m^2$ (snow live load, on the second floor)

The site seismicity level (PGA, peak ground acceleration) is:

$a_g = 0.193\ g$ (seismicity of Camerino area, Italy)

The distribution of the storey forces, with reference to the numbers of the stories and the nature of actions (seismic), is type “C”.

Ductility class of the structure assumed is “DCM” for dissipative structures under cyclic loads generated by an earthquake.

A correct estimation of behaviour factor “q” of the structure depends on ductility class and geometrical properties of the r.c. wall (storey height, width, thickness):

$H = 5.00\ m$ (interstorey height)

$B = 6.00\ m$ (width of the r.c. wall)

$s = 0.25\ m$ (thickness of the r.c. wall)

then, according to *Eurocode 8* provisions, the behaviour factor is assumed:

$q = 2.67$ (behaviour factor)

Refining the range of the *Precasteel* database about shear horizontal loads (earthquake, wind) every 100 kN, the best fitting of a dissipative r.c. wall system is reached for:

$V_b = 1300\ kN$ (base shear for a single r.c. wall)

that is related to a wall influence area of:

$A_{wall} = 606\ m^2$

Finally, the number of r.c. dissipative walls for each floor and direction (X, Y) is:

$n_{wall} = A_{CBs} / A_{wall} = 2376 / 606 \approx 4$

that is the same number as UniCAM solution for this Commercial Building structure, although in this case we are able to reduce up to 50% the extension of the steel bracing solution (width B = 12.00 m for UniCAM working example), with a remarkable saving in term of total cost.

In the following pages is briefly shown the finite element model implemented in the same way as UniCAM working example (except for the r.c. wall bracing system instead of steel bracing system), considering the same geometry, boundary and release conditions, load cases and combinations. It is interesting noticing that the pre-design *Precasteel* procedure is totally reliable, and this refined structural model is able to validate the mentioned procedure; in fact, the error estimation following the pre-design *Precasteel* procedure does not reach 15%, value that includes all the simplifications in terms of structural hypothesis (i.e. in the case of seismic actions: assuming as representative only the first vibration mode, influence of accidental eccentricity effects, combination of orthogonal load effects, etc.). It is important also underlining another important structural advantage that appears for r.c. wall bracing solutions towards steel bracing systems: all the six vibration modes (see Figure 16 ÷ Figure 21) are absolutely regular in terms of seismic mass participation components, instead of more irregular and hybrid vibration modes resulting from steel bracing solution.

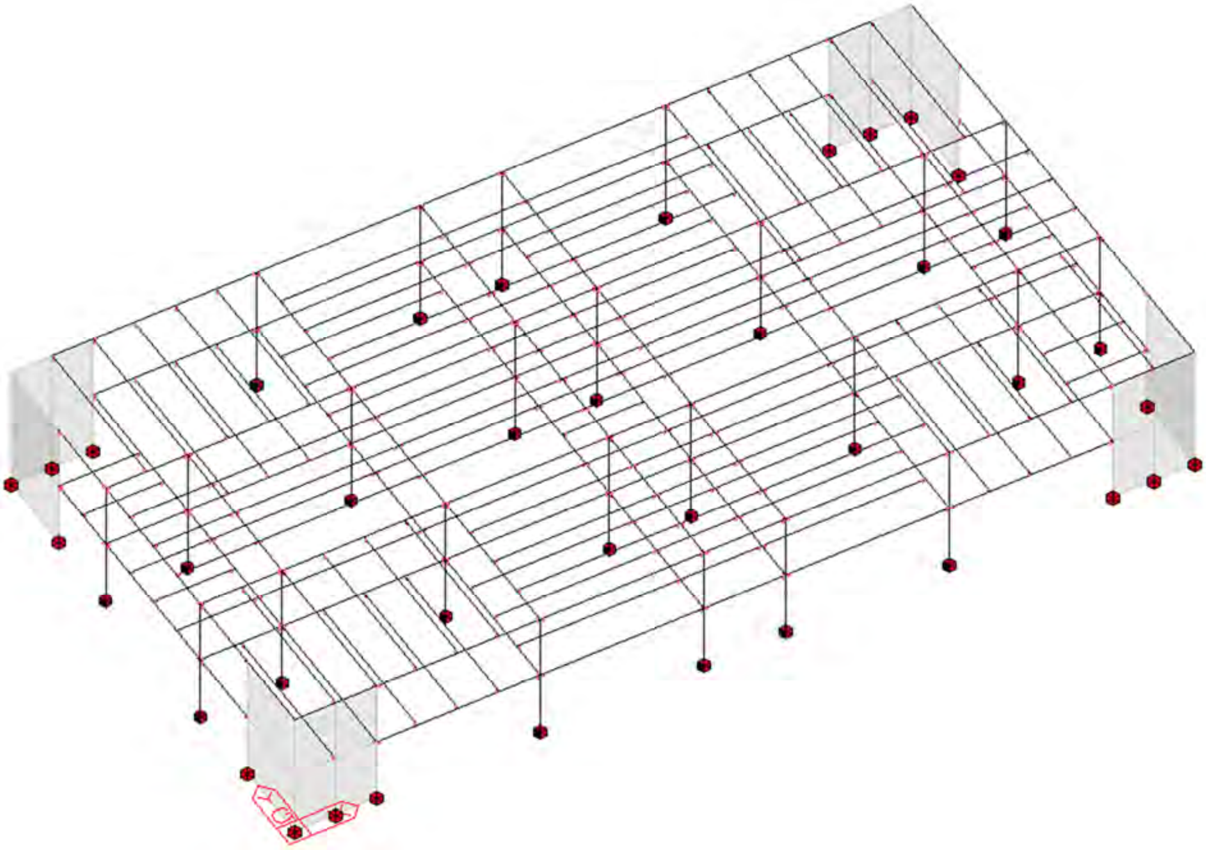

Figure 10: Case study n°3 (FeNO r.c. wall bracing system for a two-storey Commercial Building).

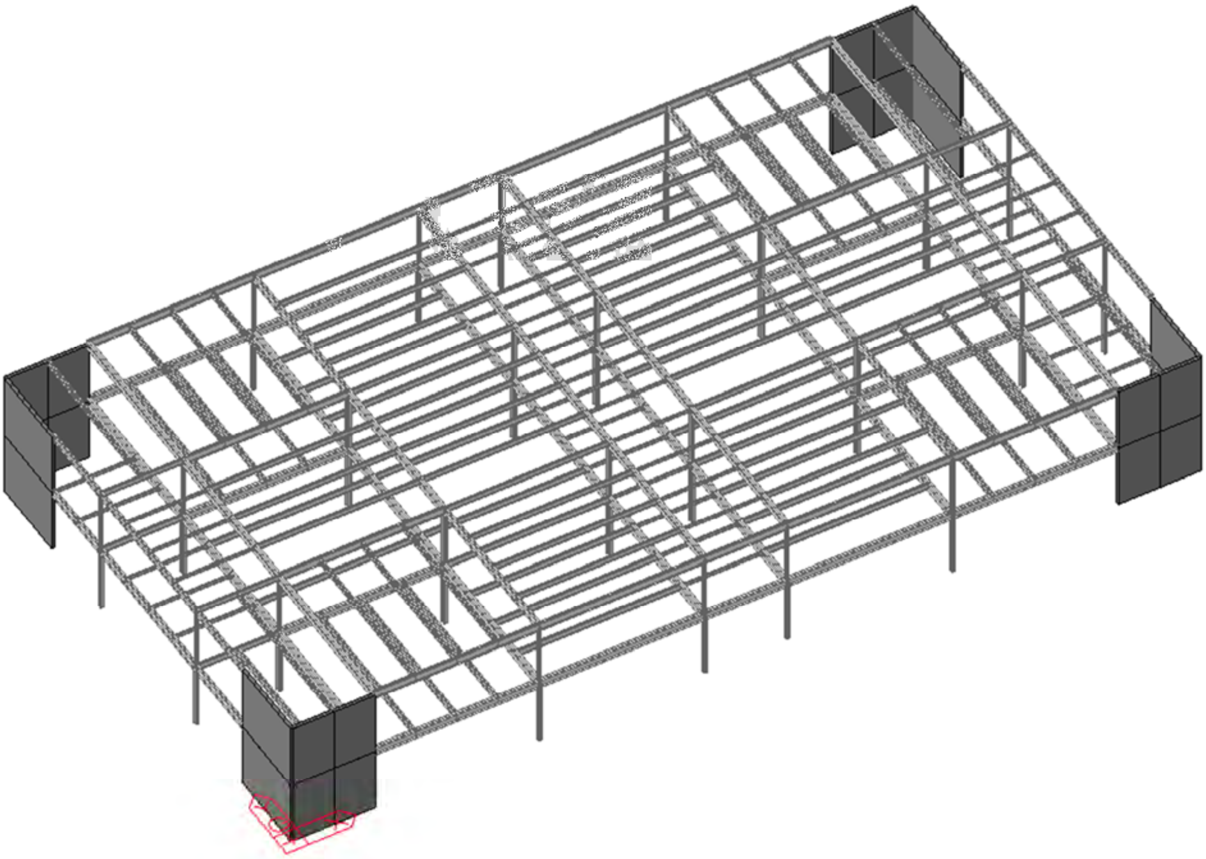

Figure 11: Case study n°3 (FeNO r.c. wall bracing system for a two-storey Commercial Building).

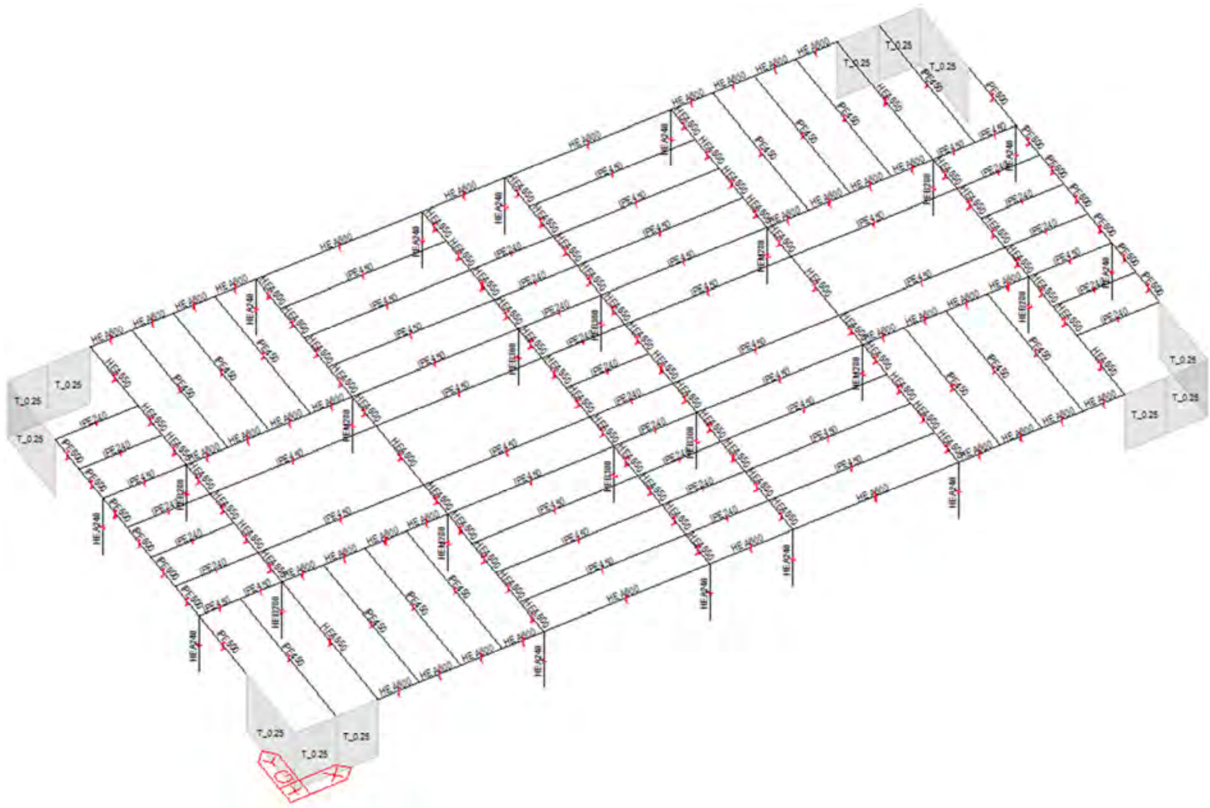

Figure 12: Case study n°3 (FeNO r.c. wall bracing system - First floor).

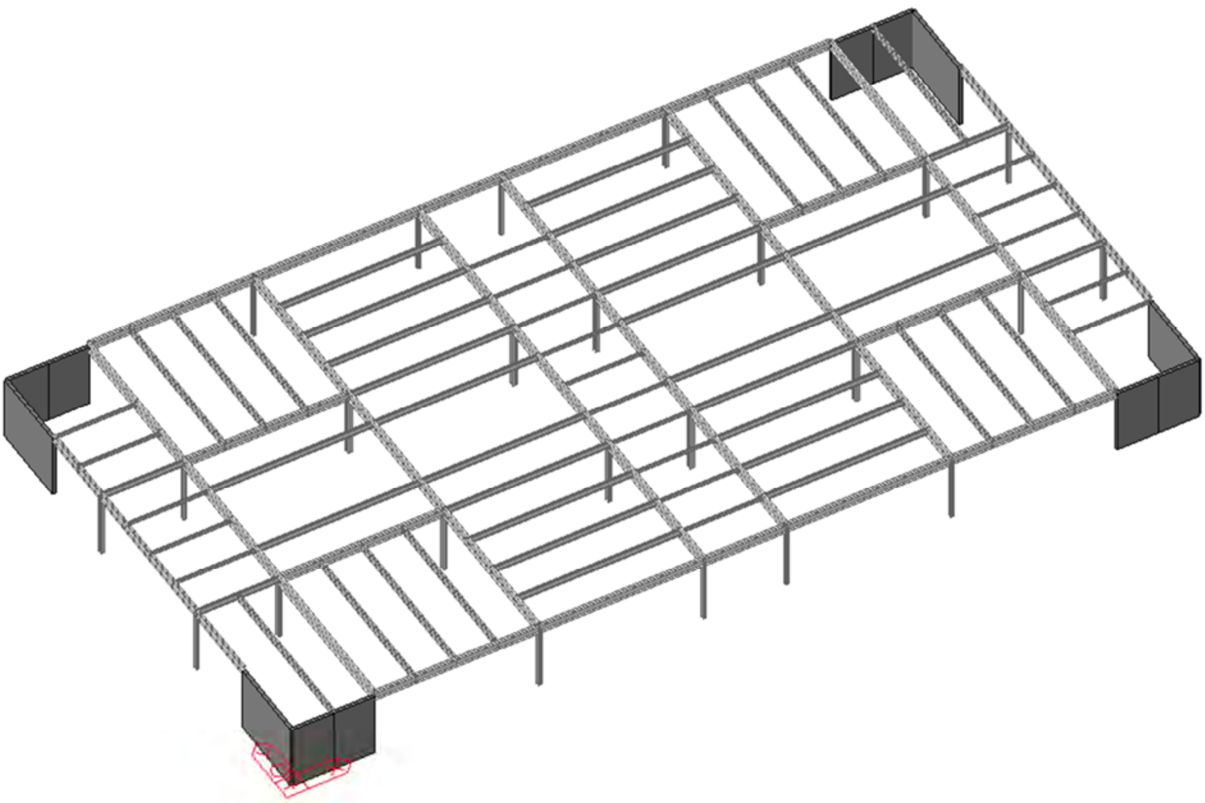

Figure 13: Case study n°3 (FeNO r.c. wall bracing system - First floor).

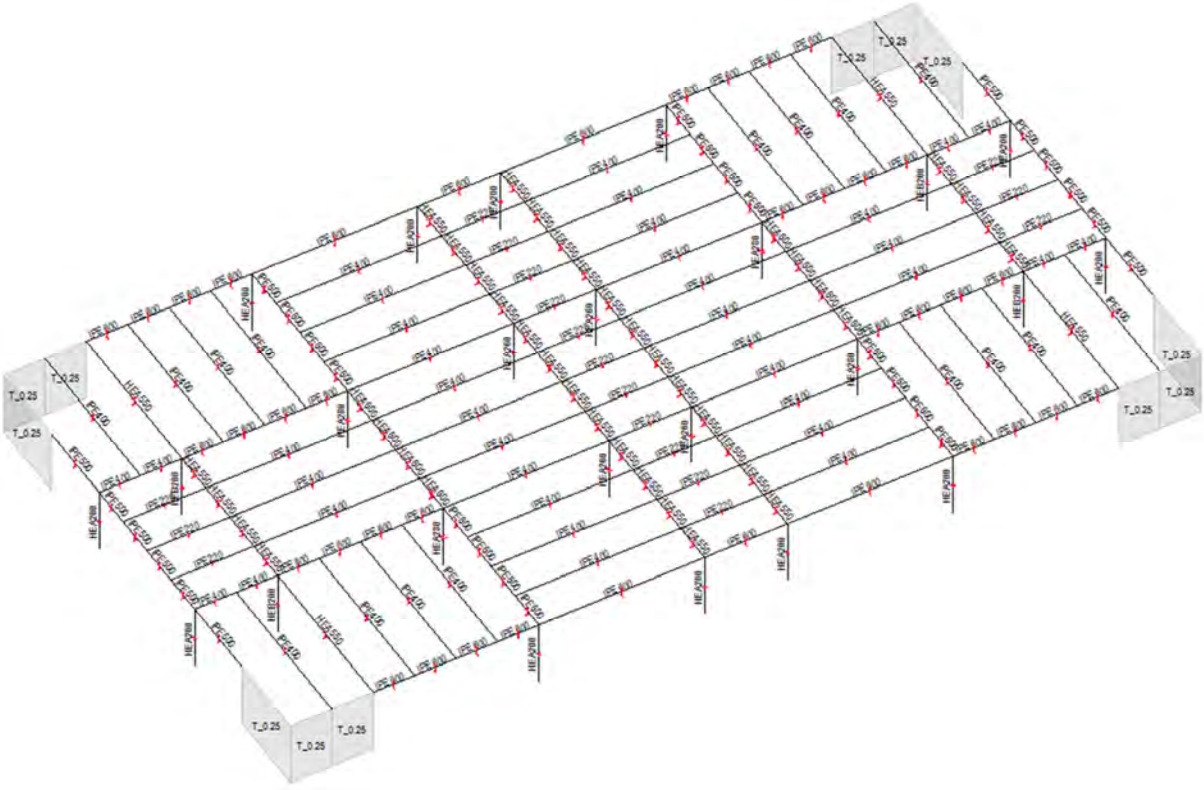

Figure 14: Case study n°3 (FeNO r.c. wall bracing system - Second floor).

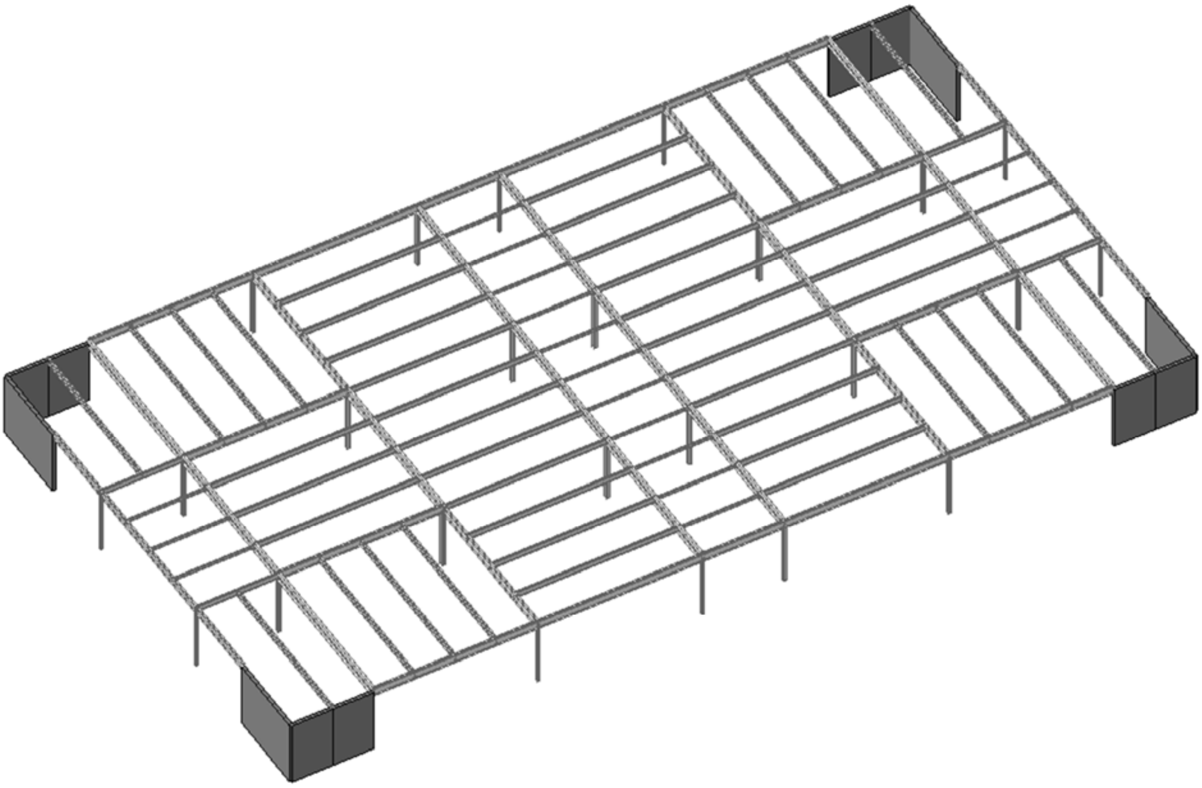

Figure 15: Case study n°3 (FeNO r.c. wall bracing system - Second floor).

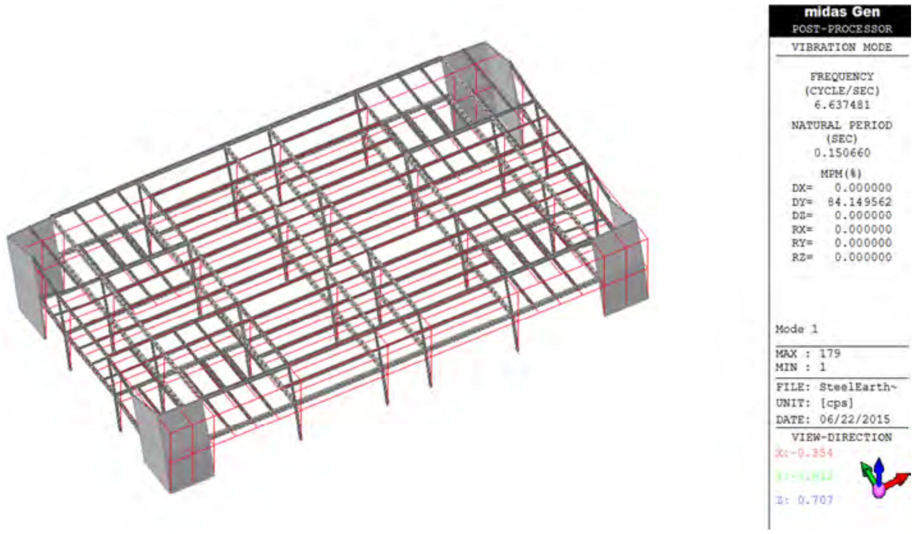

Figure 16: First vibration mode (translational Y-direction).

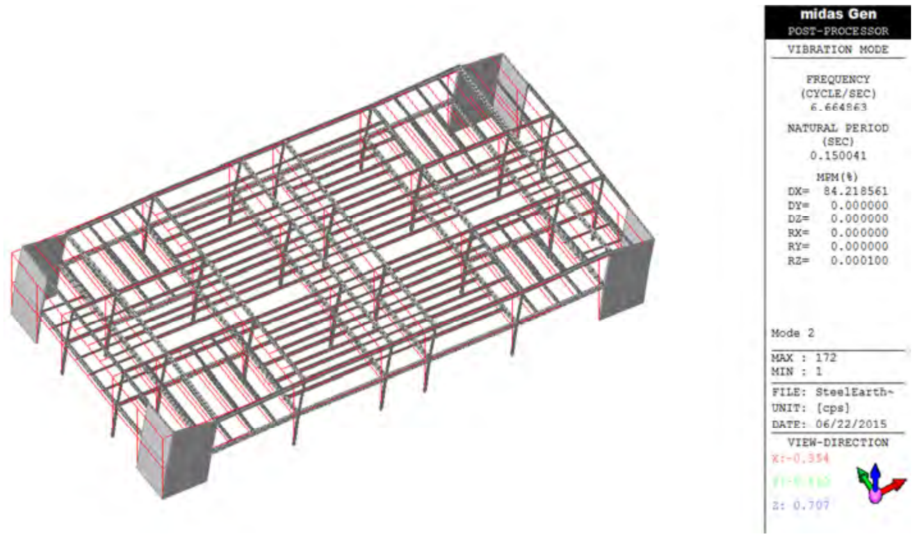

Figure 17: Second vibration mode (translational X-direction).

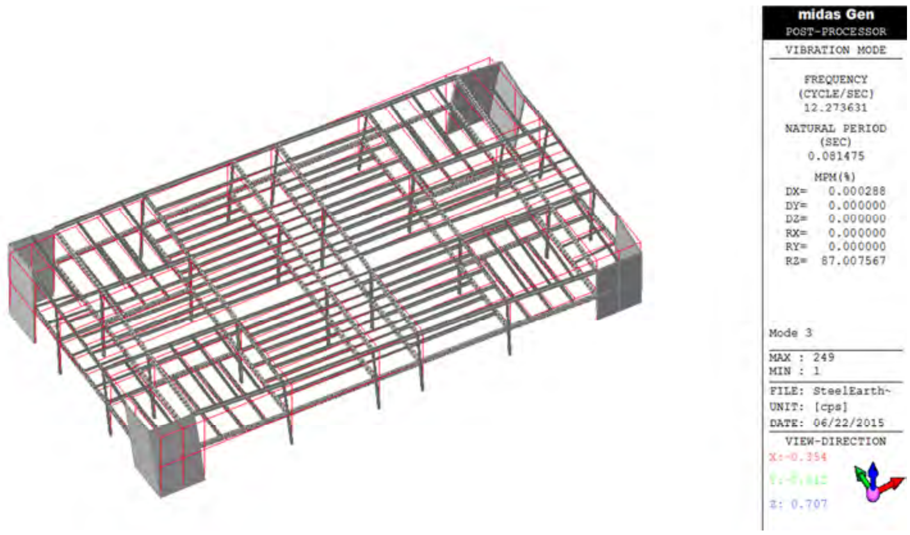

Figure 18: Third vibration mode (rotational Z-direction).

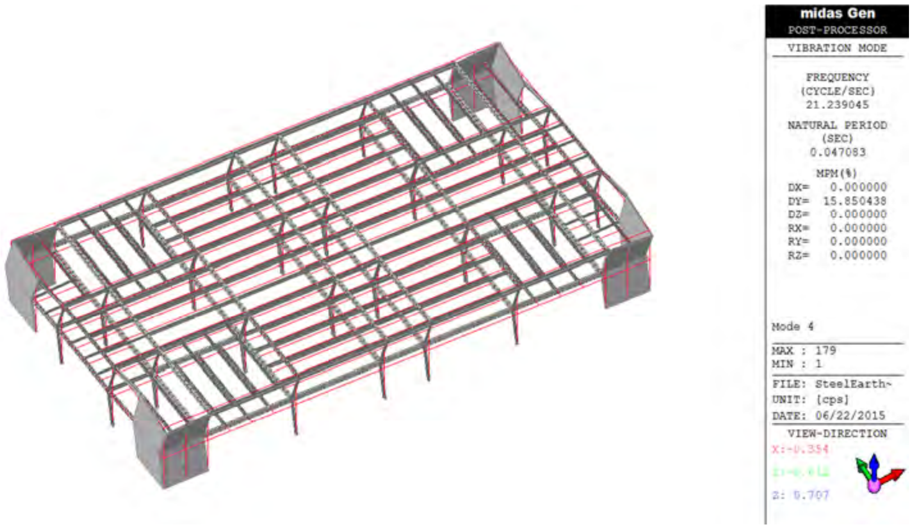

Figure 19: Fourth vibration mode (translational Y-direction).

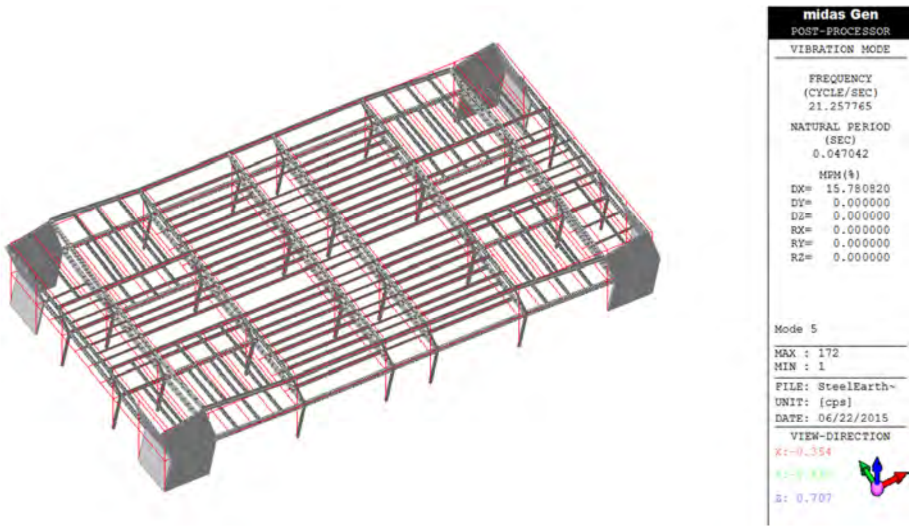

Figure 20: Fifth vibration mode (translational X-direction).

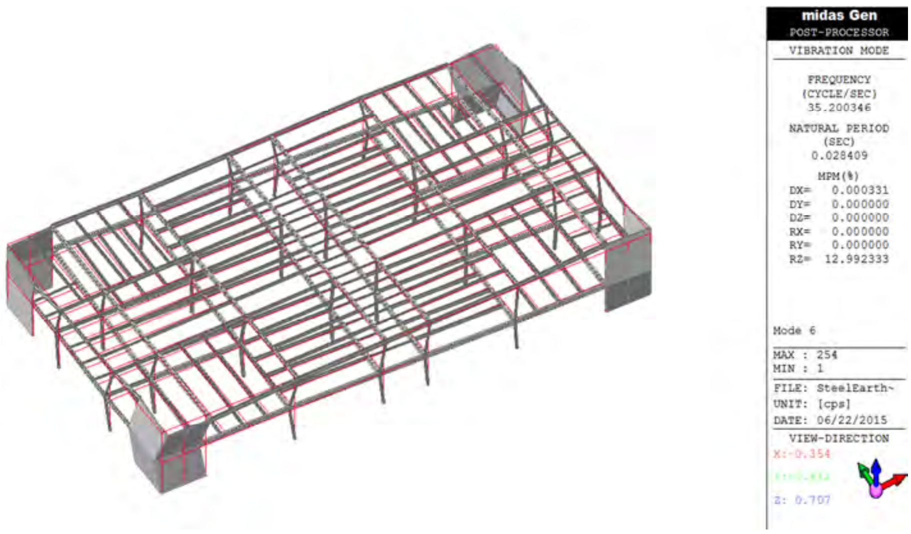

Figure 21: Sixth vibration mode (rotational Z-direction).

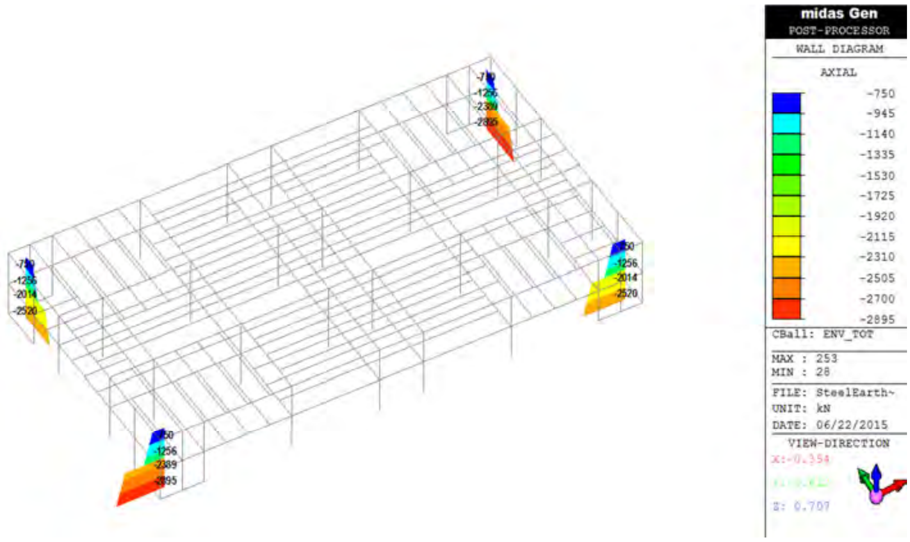

Figure 22: Envelope ULS load combination results (axial forces on r.c. wall bracing system).

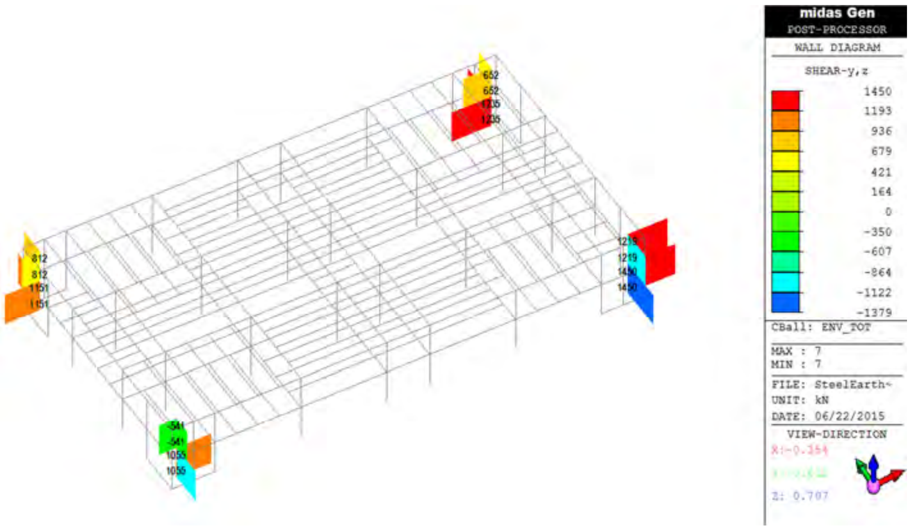

Figure 23: Envelope ULS load combination results (shear forces on r.c. wall bracing system).

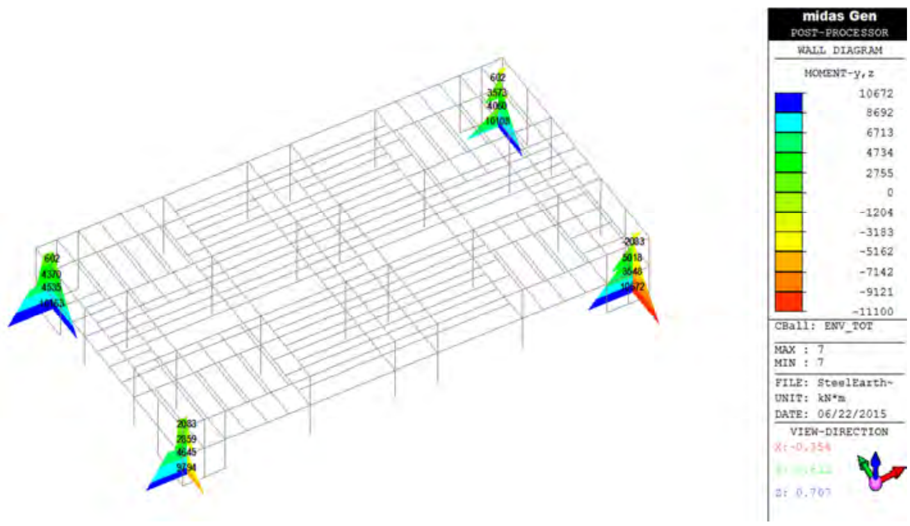

Figure 24: Envelope ULS load combination results (bending moments on r.c. wall bracing system).

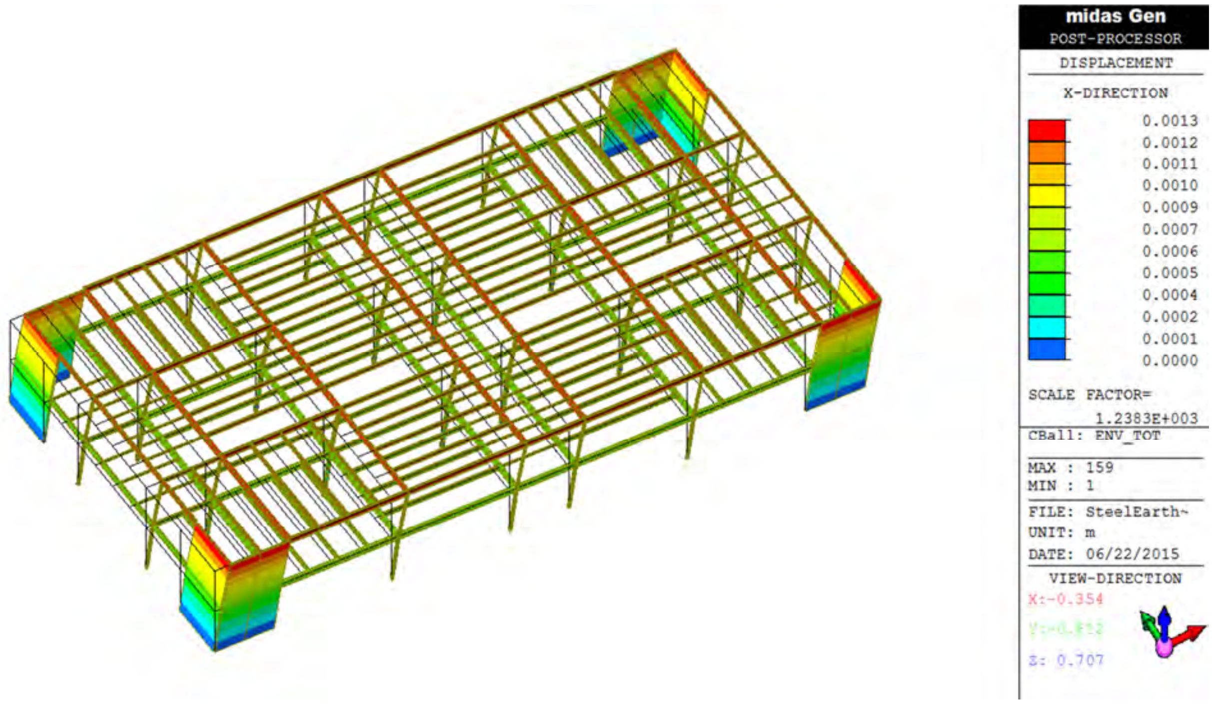

Figure 25: Envelope ULS load combination results (X-direction displacement).

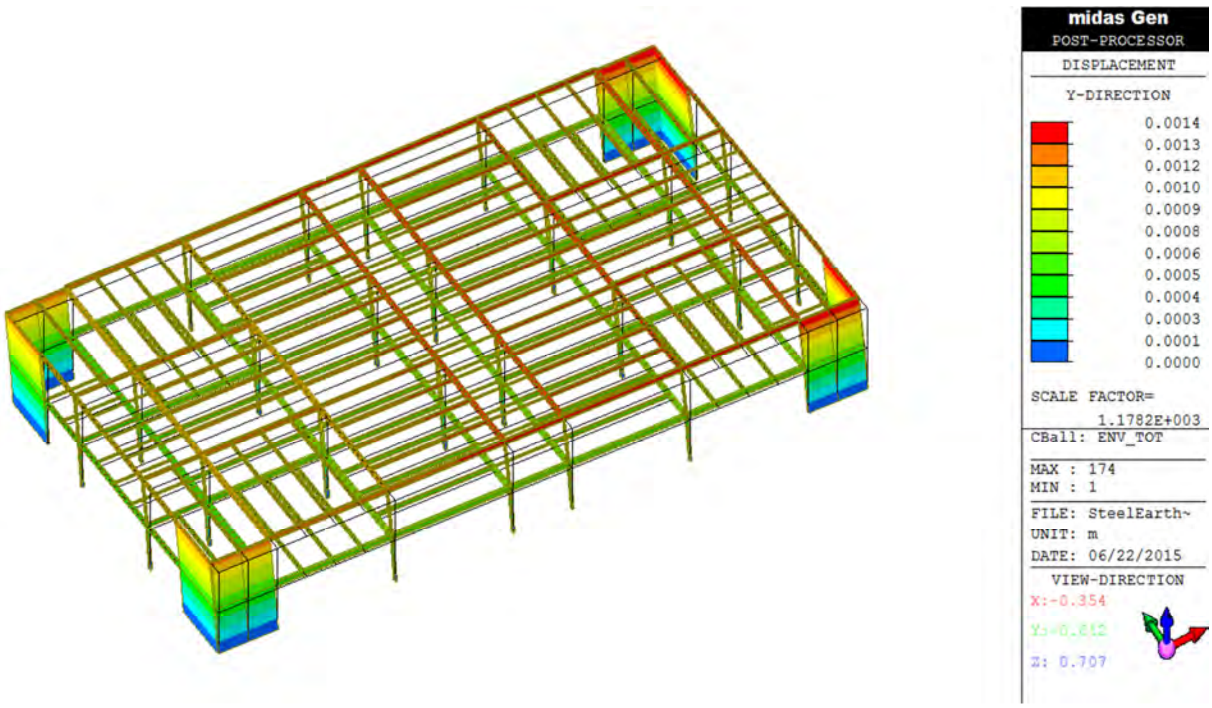

Figure 26: Envelope ULS load combination results (Y-direction displacement).

Here are reported briefly, according to *Eurocode 2* and *Eurocode 8* suggestions and provisions, all the main structural design and verifications (ULS) about r.c. wall systems.

Material properties:

concrete C30/37 (R_{ck}=37 MPa; f_{ck}=30 MPa; f_{cd}=15.94 MPa)

steel B450C (f_{yk}=450 MPa; f_{tk}=540 MPa; f_{yd}=391 MPa)

Geometrical properties:

s = 0.25 m (r.c. wall resistant thickness)

B = 6.00 m (width of the wall)

H = 5.00 m (interstorey height of the walls)

Actions and verifications (ULS) on r.c. wall system:

Axial force → N_{Ed} = 2520 kN (N.B.: compression axial force reduce up to 50% reinforcing bars percentage towards pre-design *Precasteel* procedure, due to consideration of coupling horizontal and vertical effects on r.c. wall bracing system)

Bending moment → M_{Ed} = 11100 kNm ≤ M_{Rd} = 12586 kNm

Shear force → $V_{Ed} = 1.5 \cdot V_b = 1.5 \cdot 1450 = 2175$ kN ≤ V_{Rd} = min (V_{Rsd}, V_{Rcd}) = 2523 kN

The above ULS verifications are referred to the detailed reinforcing bars and stirrups related to the following technical drawings (see Figure 27), with:

$A_{s,bending}$ = 7+7∅16 (critical region, confined zone $l_c = 0.15 \cdot B = 0.90$ m)

$A_{s,shear}$ = 1∅10/12.5cm

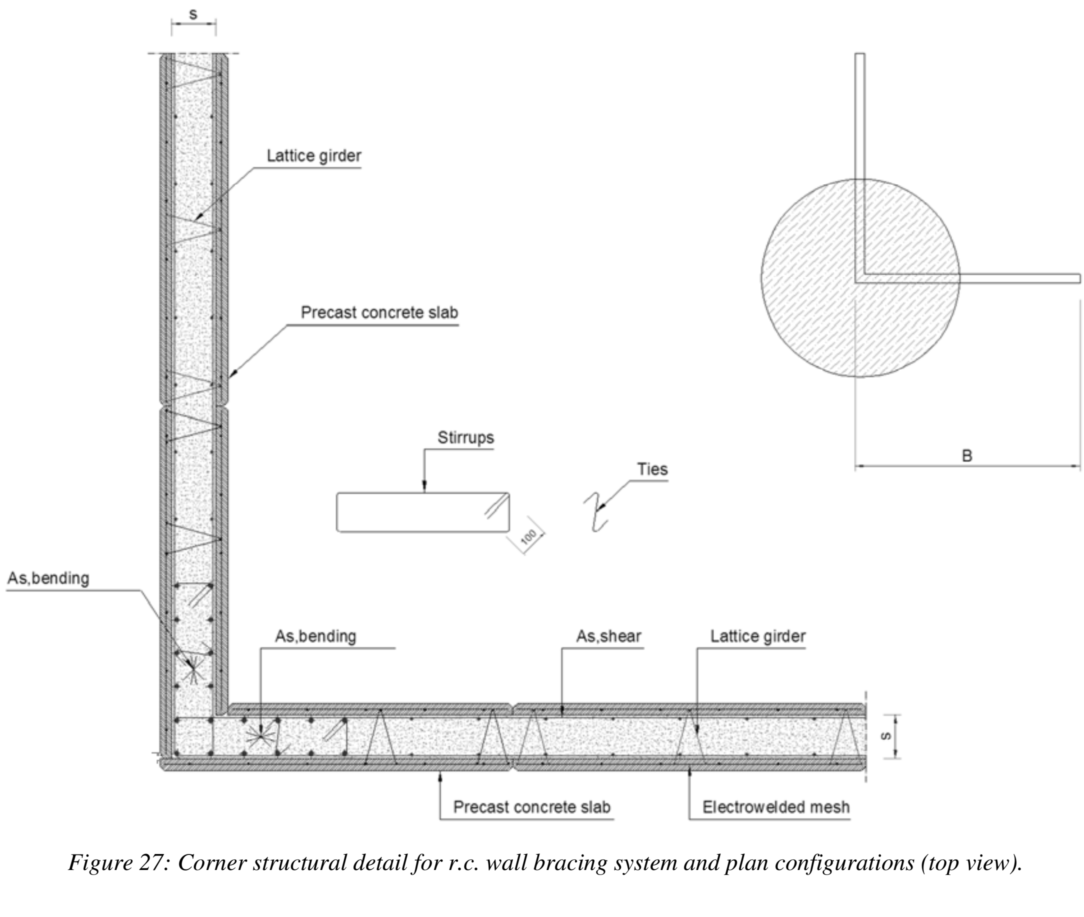

Figure 27: Corner structural detail for r.c. wall bracing system and plan configurations (top view).