EXAMPLE OF FINITE ELEMENT MODELLING

LINEAR STATIC SEISMIC ANALYSIS OF AN X-RAD SYSTEM WOODEN STRUCTURE

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1. INTRODUCTION

The following is an example of Finite Element Modelling of a structure constructed using the X-RAD system. The exercise is a detailed, step by step illustration of how to perform a linear static seismic analysis.

2. DESCRIPTION OF THE BUILDING

The analysed building has the following characteristics:

- 9 m high three-floor building;
- Plan dimensions: 14x10 m;
- Level (horizontal) plan;
- X-RAD connectors at each corner of the CLT panels;
- The partition plan is shown in Figure 1.

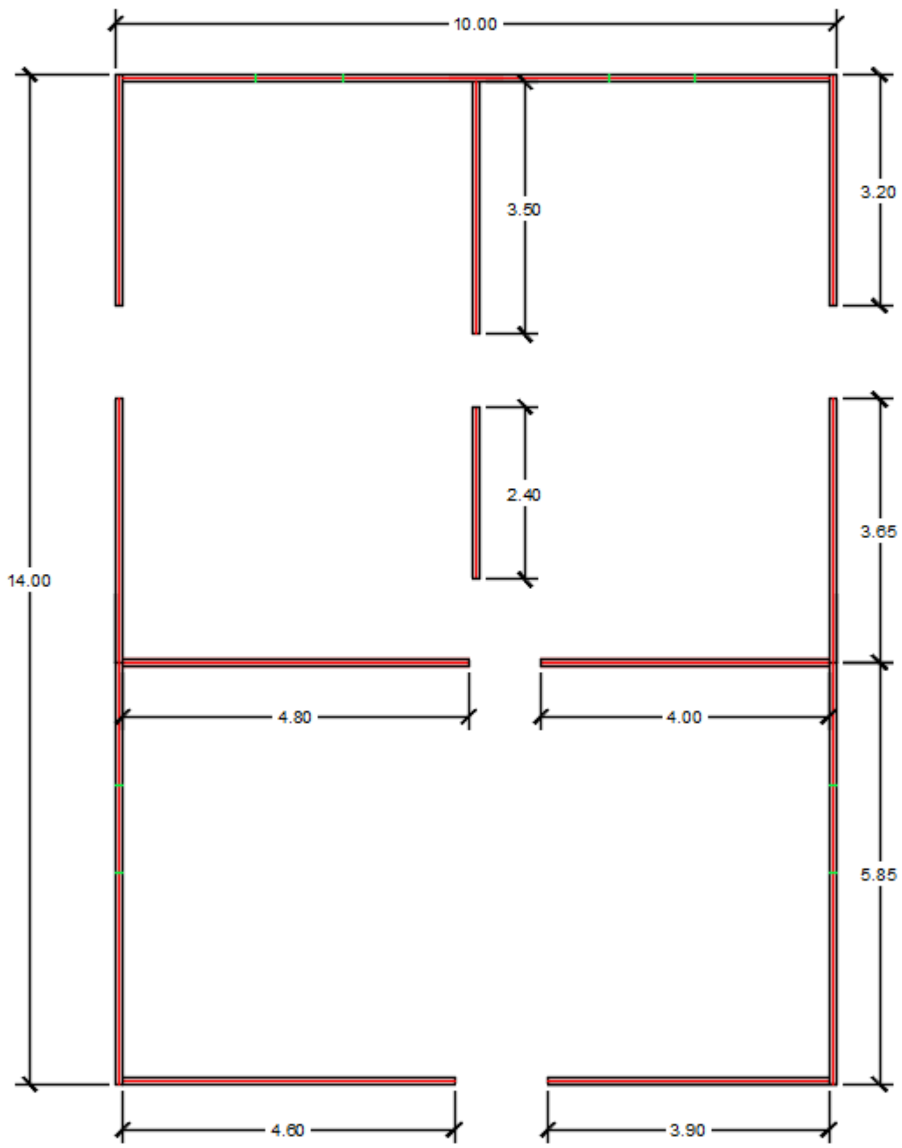

Figure 1: Plan of the Building

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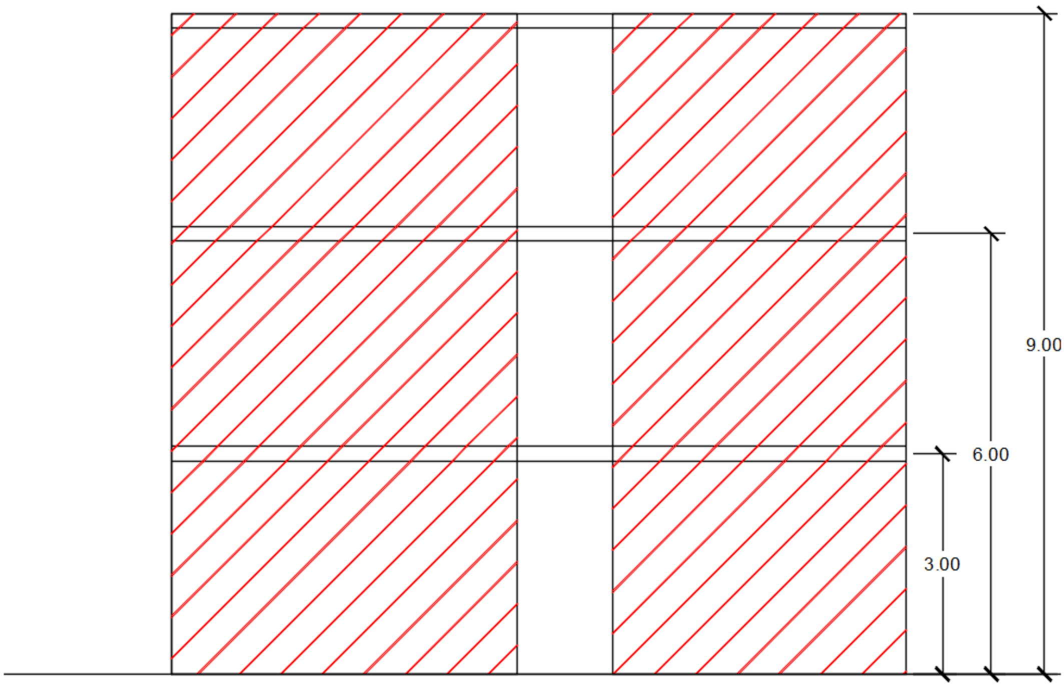

Figure 2: Elevation of the short side of the building

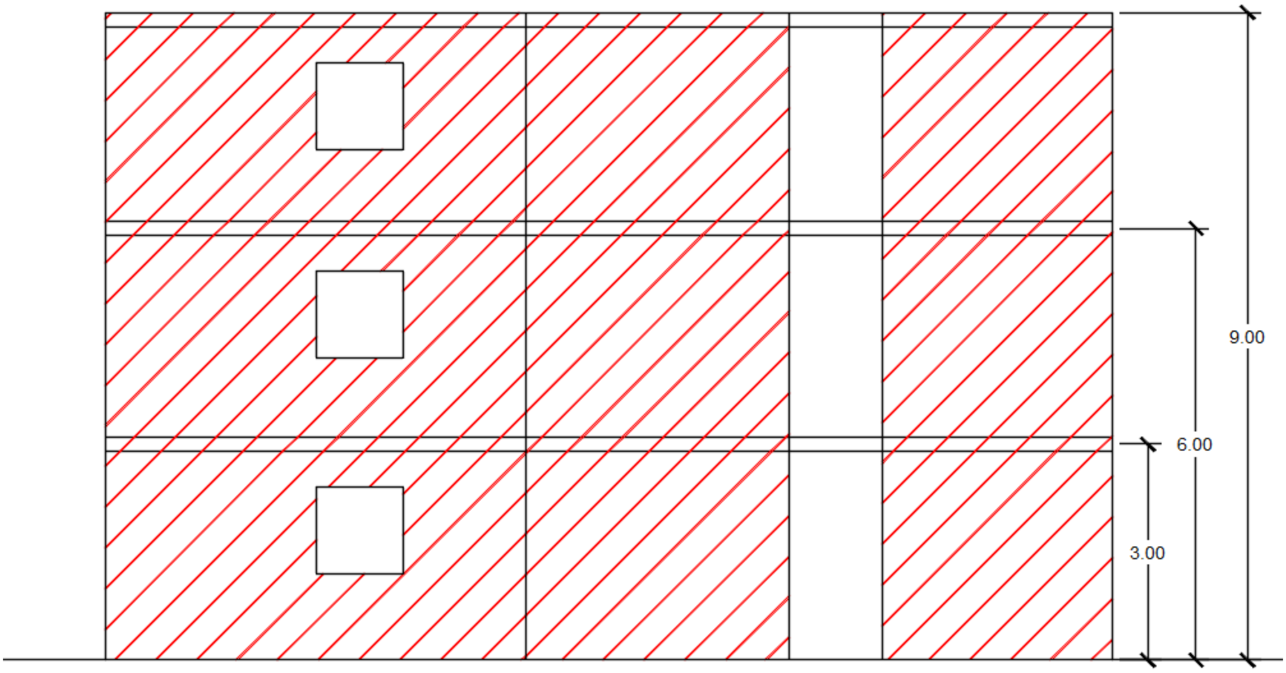

Figure 3: Elevation of the long side of the building

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3. LOAD DEFINITION

The following loads are assumed:

STATIC LOAD:

- Own weight + permanent load of decking: 3.5 kN/m^2;
- Own weight + permanent load of walls: 1.0 kN/m^2;
- Category A decking live load: 2.0 kN/m^2;

SEISMIC ACTION (Municipality of Verona):

- a_g=0.157 g;
- Underground category: C;
- Topographic category: T_2 with h/H=0.7;
- Irregular structure in height with structure factor q=1.6;

The project seismic spectrum is shown in Figure 4:

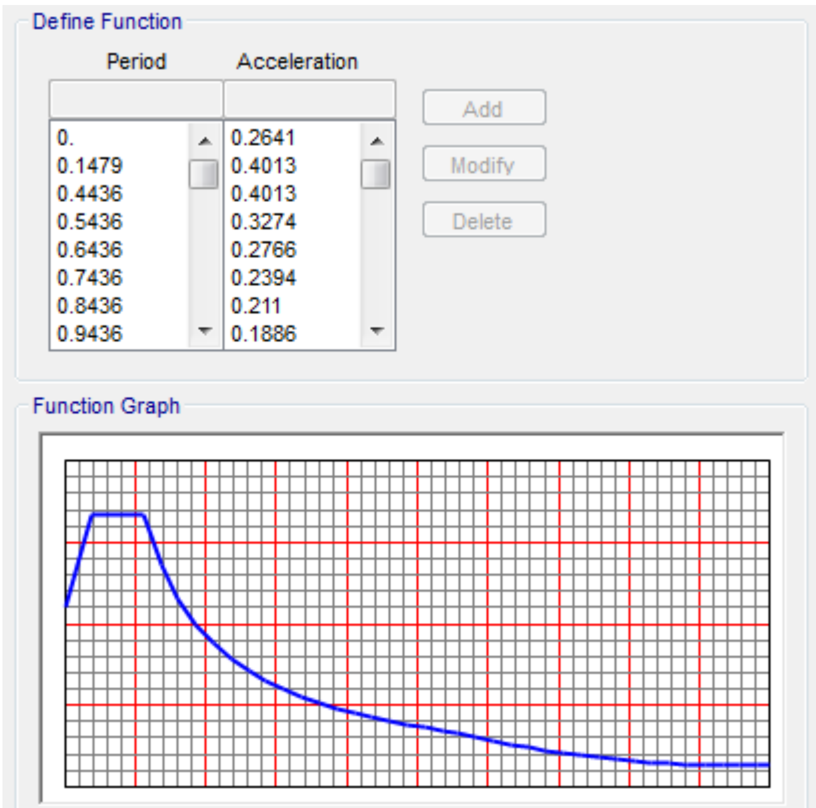

Figure 4: Project seismic spectrum

The provisions of applicable regulations (NTC08) are followed for calculating the period T_1:

$$T_1 = 0.05 \cdot H^{3/4} = 0.26\ s$$

We are therefore in the plateau section of the spectrum shown in Figure 4 and consequently:

$$S_d(T_1) = 0.4013\ g$$

By way of example the results of 9 different load combinations will be given as shown in the following table:

Table 1: Load combinations:

COMB. NUMBER	TYPE OF COMBINATION
1	Static ULS
2	life safety limit state +100%X + 30%Y
3	life safety limit state +100%X + 30%Y
4	life safety limit state -100%X + 30%Y
5	life safety limit state -100%X + 30%Y
6	life safety limit state +30%X + 100%Y
7	life safety limit state +30%X + 100%Y
8	life safety limit state -30%X + 100%Y
9	life safety limit state -30%X + 100%Y

The action of wind and the 5% displacement of the centre of gravity of the seismic masses are therefore not taken into account.

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4. BUILDING A FINITE ELEMENT MODEL

The basic element of the model has an X-RAD at each corner of a CLT panel.

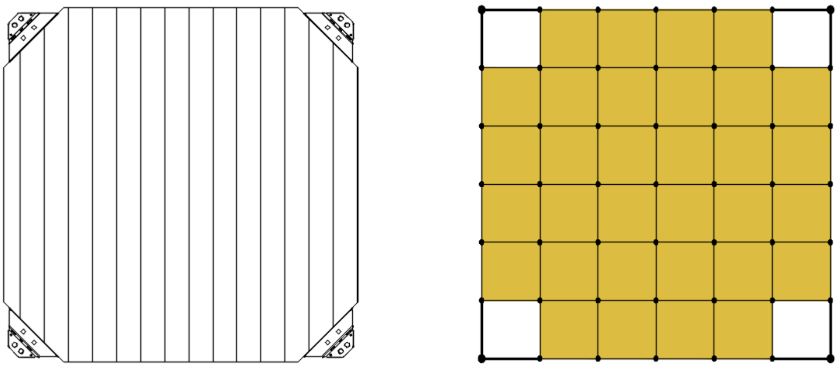

Figure 5: Basic element of the model

The connector has two 255 mm long steel connecting rods with a 5.51 mm side square cross section ("frame" elements at the corners of the panel in Figures 5 and in Figure 6). In this way a final stiffness of the X-RAD connection of k=25 kN/mm is obtained. The CLT panel is made of "shell" type of elements (isotropic material with an elastic modulus E=5500 MPa). Such simplified schematic representation of the CLT material is justified considering that the stiffness of the CLT-XRAD system is governed by the deformability of the connection.

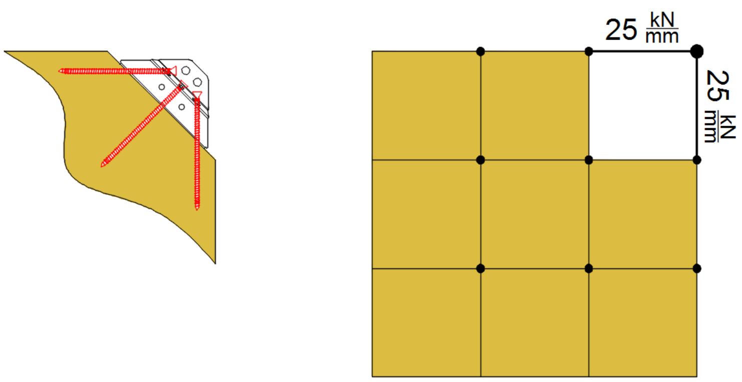

Figure 6: Detail of X-RAD made up of "frame" type of elements

A choice was made to represent each X-RAD with two connecting rods in order to associate a traction/compression force with the vertical frame element, while a shear force is associated with the horizontal frame element (see Figure 7).

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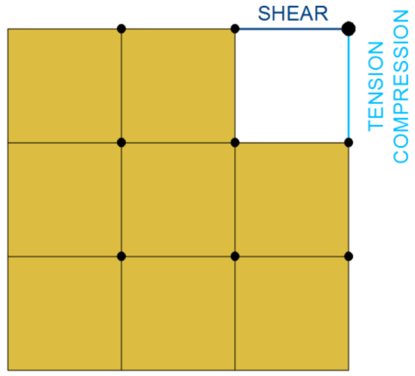

Figure 7: Forces associated with the two "frame" elements

Gap type nonlinear springs are defined to simulate the panel to panel and the panel to foundation contact. These have an infinite rigidity upon compression and no resistance to traction. They are schematically represented in green with a letter C next to them in Figure 8.

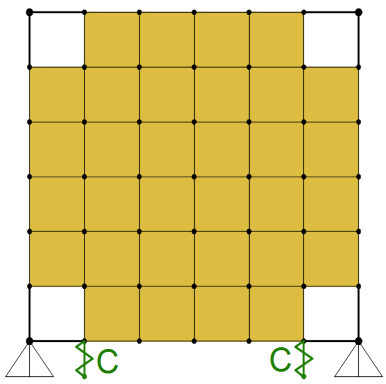

Figure 8: "Gap" type springs that are infinitely rigid upon compression

A spring is placed at each end of the panel, both vertically and horizontally (simulating the contact between CLT panels and they are shown in light green in Figure 9). The springs at the base of the walls simulate the panel-foundation contact (dark green).

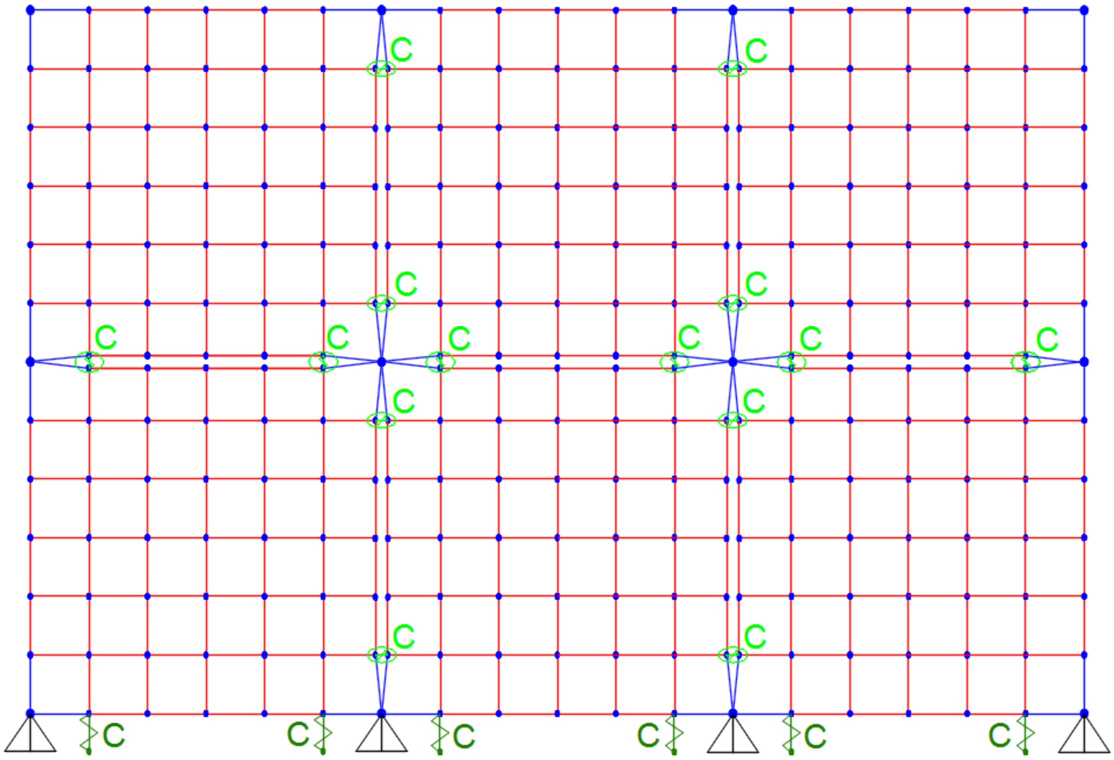

Figure 9: An example of an array of springs

In order to distance the CLT panels from each other, the connecting rods simulating the connector have to be slightly inclined as shown in Figure 9. It has been demonstrated that such inclination involves an error of less than 4% in terms of forces exerting on each X_RAD, and therefore acceptable from an engineering point of view.
And now let us look at the four different X-RAD configurations that are used in a building with their relative finite element models:

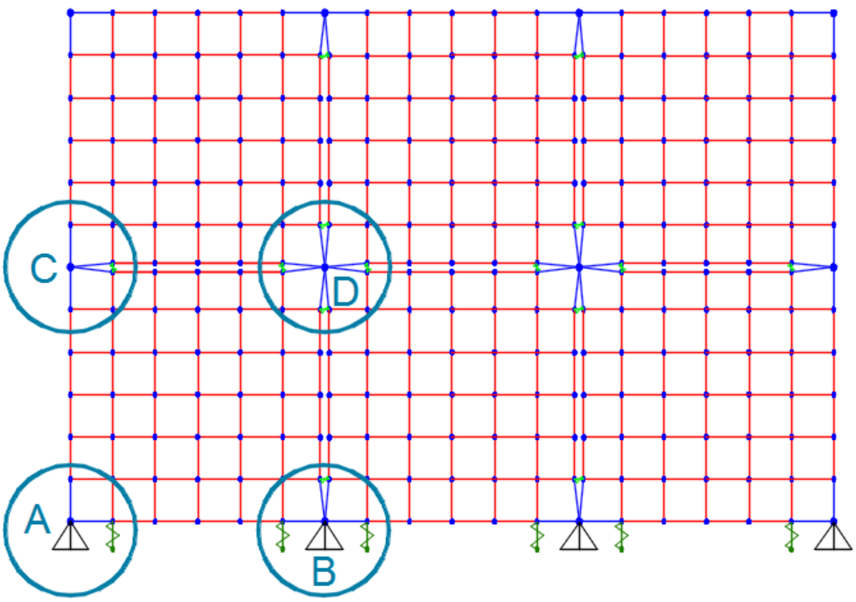

Figure 10: Four possible X-RAD configurations

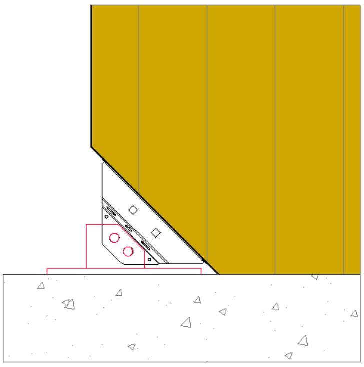

Figure 11: One link configuration (A in Figure 10)

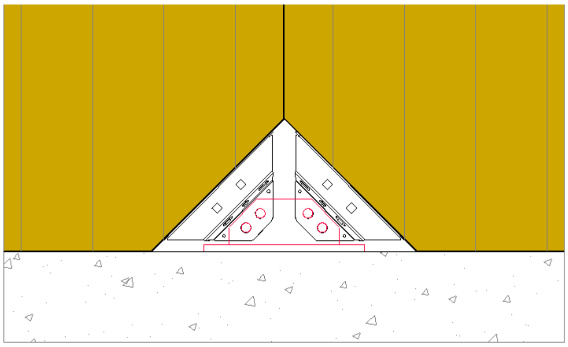

Figure 12: Two horizontal links configuration (B in Figure 10)

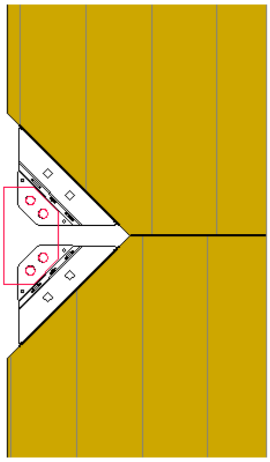

Figure 13: Two vertical links configuration (C in Figure 10)

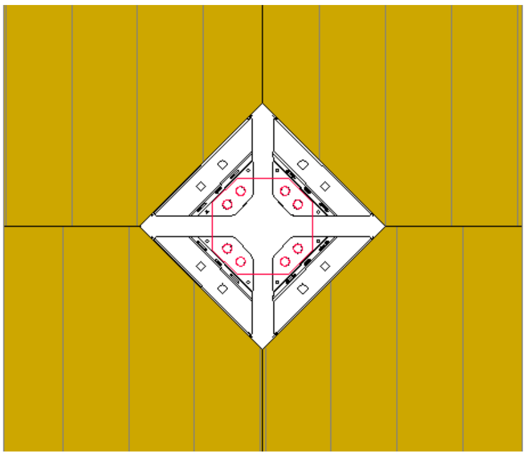

Figure 14: Four links configuration (C in Figure 10)

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Rigid diaphragms have been inserted at each floor in order to give all the points that are connected to the floor the same horizontal displacement. This constraint is a model for floor bracing made up of CLT floor panels appropriately attached to each other. In order to avoid implementation errors it is important to exclude the X-RAD nodes from the horizontal diaphragm (the black nodes in Figure 15 are part of the diaphragm, while the red X-RAD nodes are excluded).

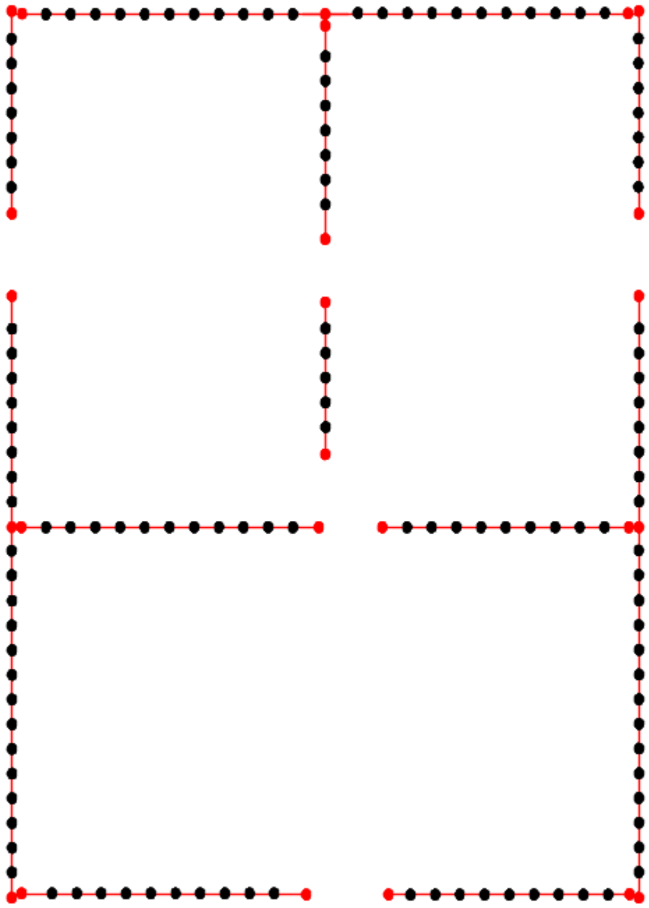

Figure 15: Definition of horizontal diaphragms

It is assumed that panels that are perpendicular to each other are not joined. The panels that in a real construction connect perpendicular walls are inserted as a construction connection outside the scope of the calculation.

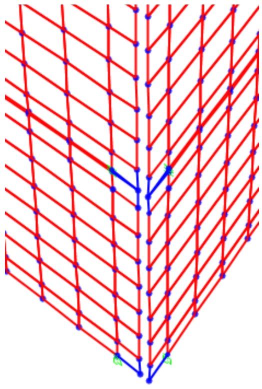

Figure 16: Disjuncture of perpendicular panels

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Regarding the introduction of loads in the model, there is a choice between two different methodologies:

- Loads can be added directly at the points of the "shell" elements of the walls where the floors rest on;
- Elements known as "load-bearing beams" can be defined for such purpose paying attention to release them from the moment effect in the nodes (they act as connecting rods).

Regarding the modelling of any beams or lintels in the building, it is possible to define connecting rods (example of a lintel shown in blue in Figure 17).

And this leads to the final definition of the model:

- 3D VIEW

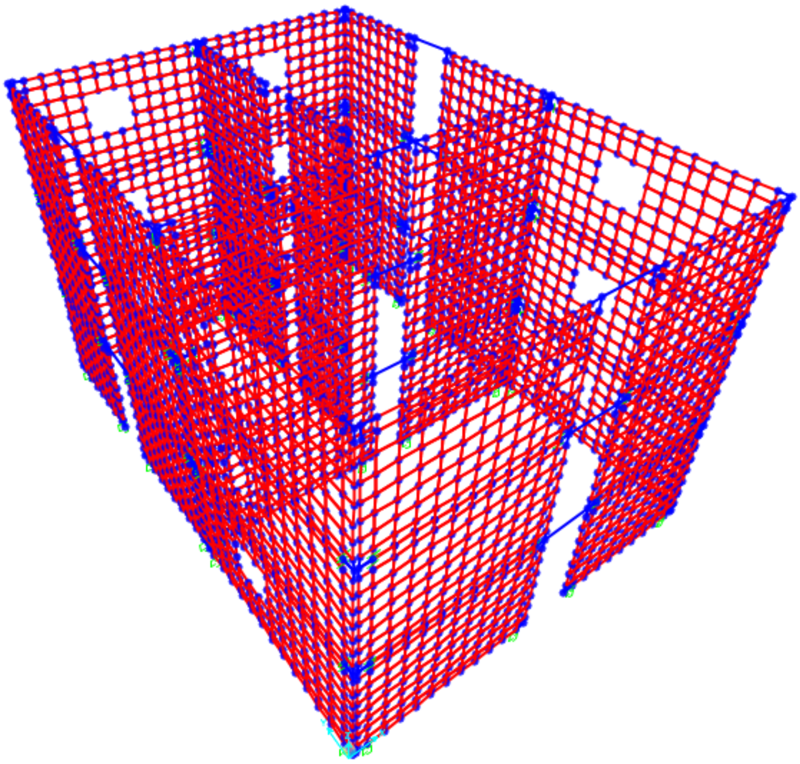

Figure 17: 3D view of the finished model

- EXAMPLES OF A "WALL SYSTEM"

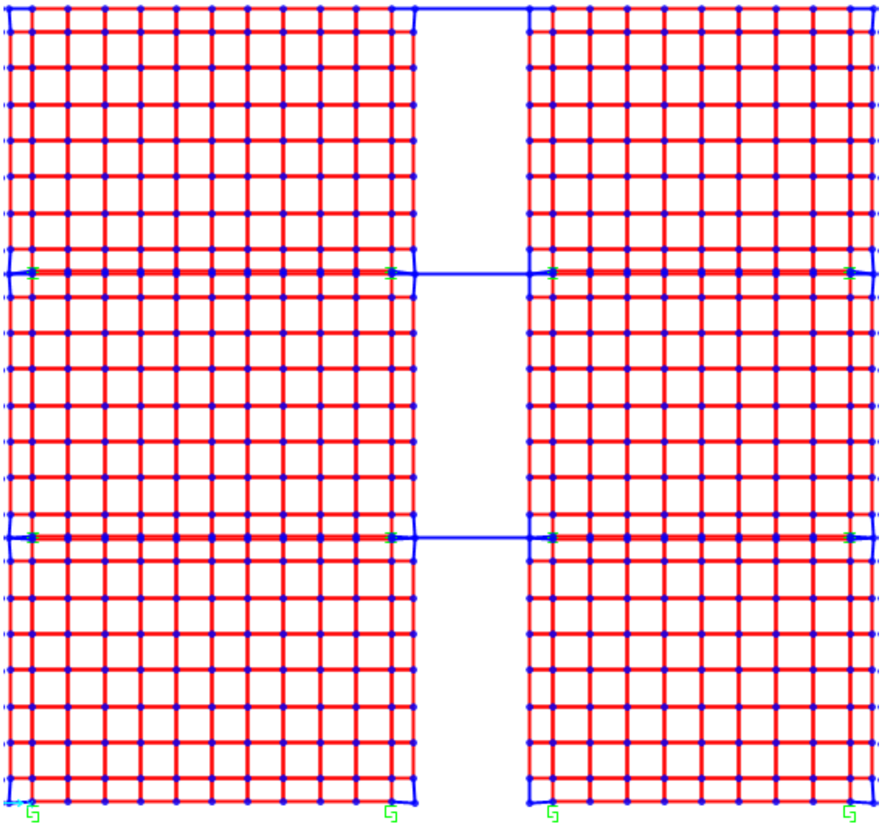

Figure 18: Short side external wall model

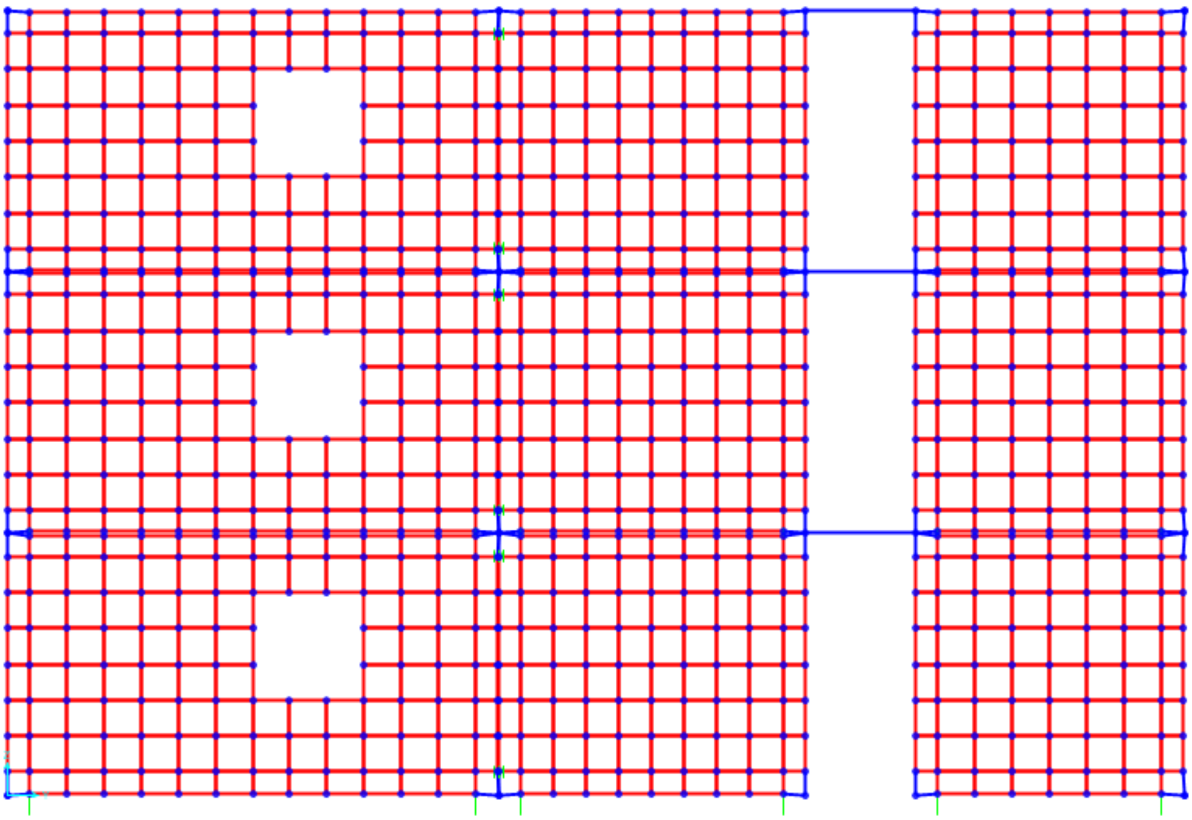

Figure 19: Long side external wall model

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5. CALCULATION OF THE FORCES ACTING AT EACH NODE

The flow diagram below is used to calculate the forces acting on each connector, as required in the checking phase.

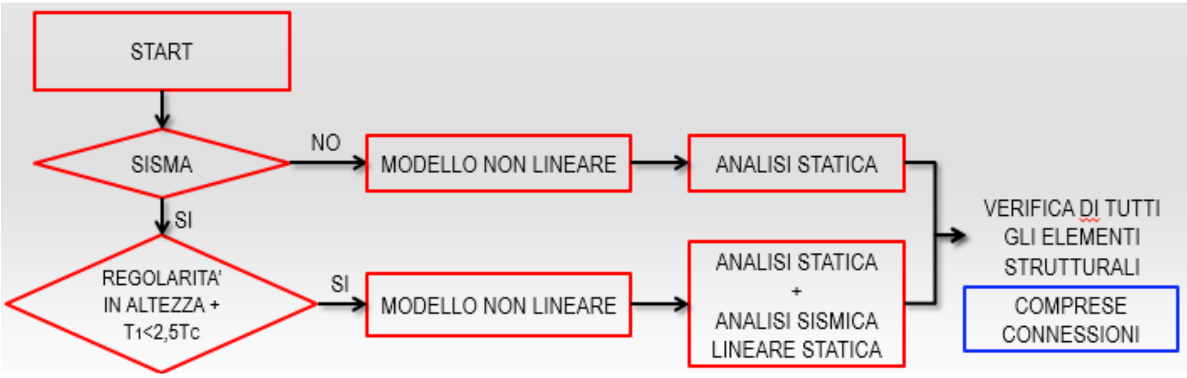

Figure 20: Flow diagram

START	START
SISMA	EARTHQUAKE
SI / NO	YES / NO
REGOLARITA IN ALTEZZA + T1<2,5Tc	REGULAR HEIGHT + T1<2.5Tc
MODELLO NON LINEARE	NON-LINEAR MODEL
ANALISI STATICA	STATIC ANALYSIS
ANALISI STATICA + ANALISI SISMICA LINEARE STATICA	STATIC ANALYSIS + STATIC LINEAR SIESMIC ANALYSIS
VERIFICA DI TUTTI GLI ELEMENTI STRUTTURALI COMPRESE CONNESSIONI	CHECK ALL STRUCTURAL ELEMENTS INCLUDING CONNECTIONS

The analysis provides a NON-LINEAR method for resolving the finite element model give the presence of springs that only function under compression as previously described. Once the external forces have been defined and the various load combinations carried out, the axial forces acting on each connecting rod can be derived from the FEM program output. As already mentioned, there are traction / compression forces associated with the vertical connecting rods and shear forces on the horizontal ones (Figure 7).

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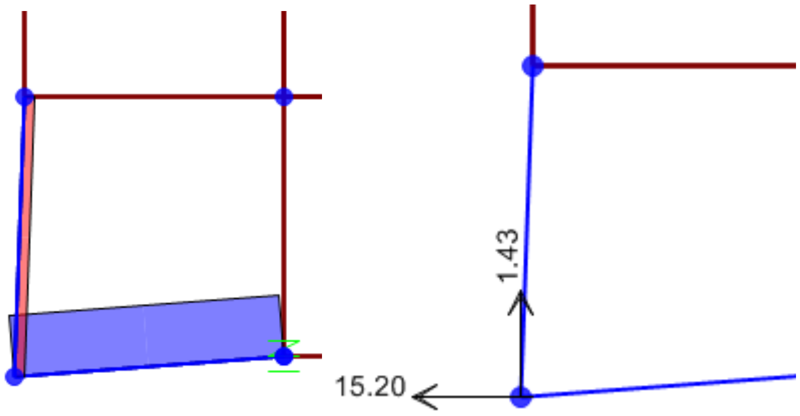

Figure 21: Example of exertion of a force on a foundation X-RAD

The X-RAD in Figure 21 is subjected to a force of compression (in red) of 1.43 kN and a shear force (in blue) of 15.20 kN.
In order to check the connector it is necessary to add up these two forces and check that the resultant force is within the breaking point. This step is facilitated with the use of "MyProject" software which is made available to designers and which can be downloaded from the www.rothoblaas.com site. In particular, for each X-RAD, all it takes is to copy the tables with the two forces (shear force and traction/compression force) and provide them as input to the software program. The software will then automatically carry out a check of the X-ONE connector.

Figure 22 shows how the connectors that are subjected to greater force are those in the foundations. In the case under consideration, if the checks prove to be successful at the ground floor, then the X-RADs of the upper floors will also pass the test.

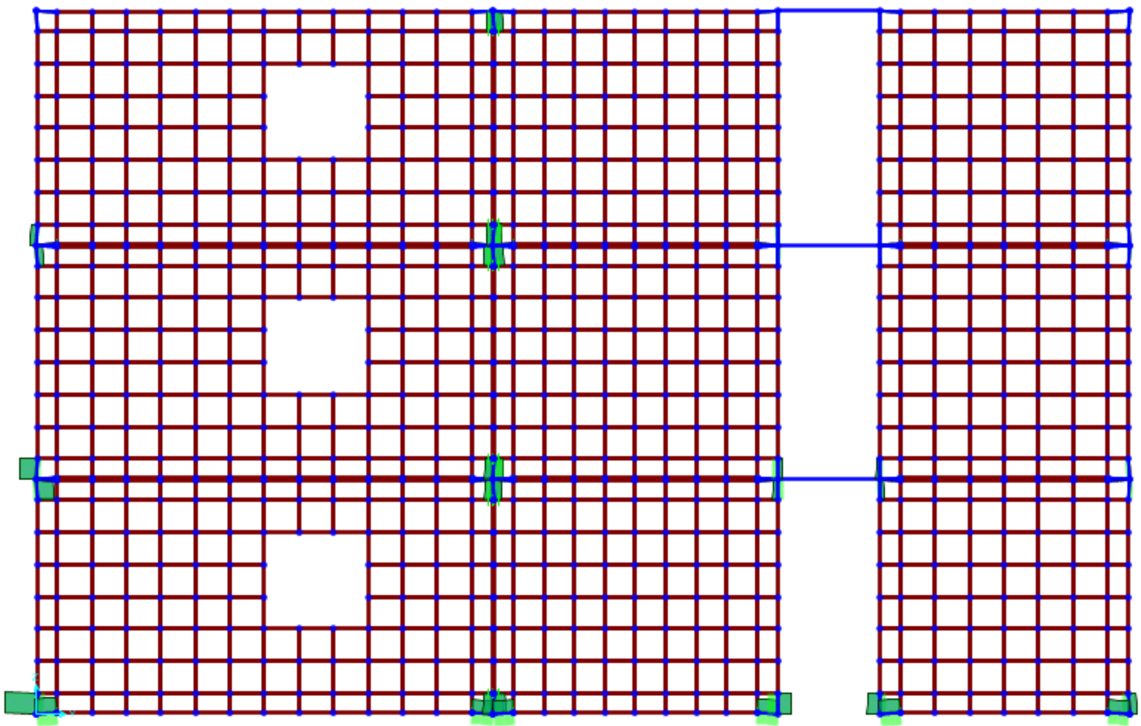

Figure 22: Exertion of forces on a wall system

6. CHECKING THE X-ONE CONNECTOR

Once the forces acting on each X-RAD have been exported from the finite element model, checking the connectors is a trivial matter. Indeed, MyProject software carries out the check automatically when the shear (Vd) and axial (Nd) forces are entered in the appropriate table. Traction forces are entered as positive values and compression forces as negative. It is possible to enter any number of combinations of forces, with each one being associated with a specific load combination as provided by the regulations.
The exercise of checking the X-RAD foundation connector shown in green in Figure 23 is illustrated below as an example.

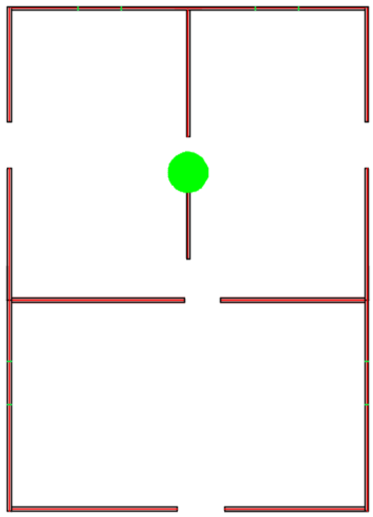

Figure 23: The X-RAD connector under examination

The forces acting on this connector for each load combination are shown in Table 2.

Table 2: Exerted forces for the various load combinations:

TYPE OF COMBINATION	Vd [kN]	Not available [kN]
Static ULS	0.8	-22.2
life safety limit state +100%X + 30%Y	-12.3	-17.3
life safety limit state +100%X + 30%Y	11.6	-8.3
life safety limit state -100%X + 30%Y	-12.3	-17.3
life safety limit state -100%X + 30%Y	11.6	-8.4
life safety limit state +30%X + 100%Y	-38.4	-33.9
life safety limit state +30%X + 100%Y	38.7	14.9
life safety limit state -30%X + 100%Y	-38.4	-33.9
life safety limit state -30%X + 100%Y	38.7	14.9

These pairs of force exertions must be entered in the "MyProject" software input table as shown in Figure 24.

canc	Nr. coppia	Componente Vd [kN]	Componente Nd [kN]	Risultante Fd [kN]	Angolo α [°]
	1	0.80	-22.20	22.21	272.06°
	2	-12.30	-17.30	21.23	234.59°
	3	11.60	-8.30	14.26	324.42°
	4	-12.30	-17.30	21.23	234.59°
	5	11.60	-8.40	14.32	324.09°
	6	-38.40	-33.90	51.22	221.44°
	7	38.70	14.90	41.47	21.06°
	8	38.40	-33.90	51.22	318.56°
	9	38.70	14.90	41.47	21.06°

Figure 24: "MyProject" input table with 9 load combinations

The program automatically reads the input data and for each load combination carries out a check that is illustrated in numerical and graphical format.
In the example under consideration the connector checks out positively for all the load combinations.

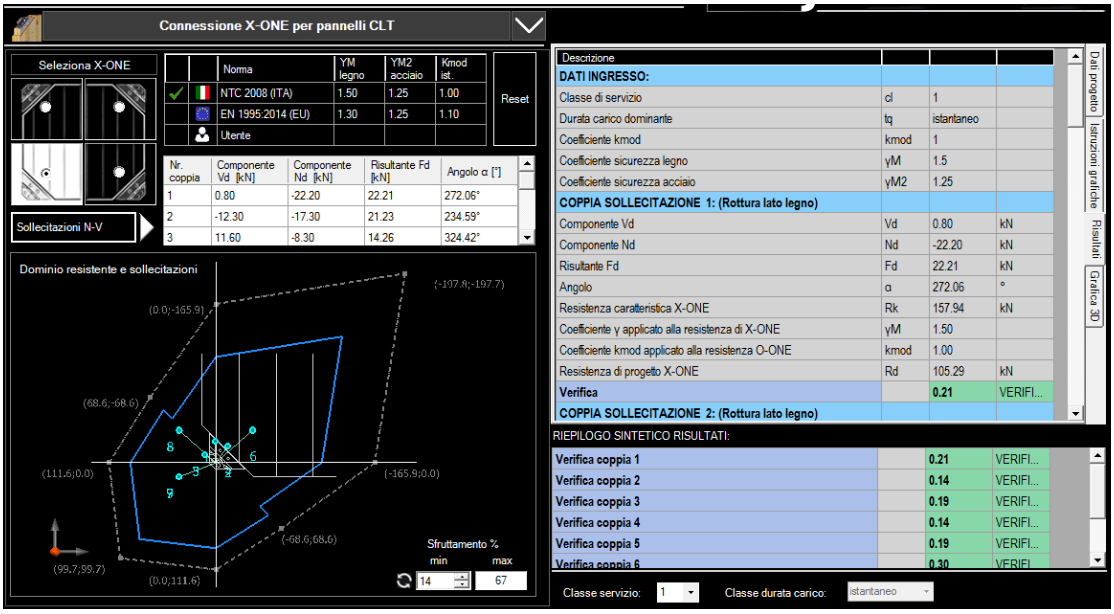

Figure 25: "MyProject" connector check

The graph in Figure 25 shows how all the points representing the resultant force acting on the connector fall within the area delimited by the blue outline which represents the breaking point.