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SHAKING TABLE TEST CHALLENGES FOR A LIGHTWEIGHT CONCRETE STRUCTURE

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Abstract: *Under the frame of the ERIES transnational access opportunity, the ECORE project has been funded during the first call. A two level structure having an irregular plan layout of about 4 × 4 m is subjected to dynamic tests on the AZALEE shaking table at CEA Paris Saclay. Lightweight concrete slabs and beams join normal weight concrete columns and autoclaved aerated concrete (AAC) external walls. Partition walls with a recoverable decoupling system from the upper beam are built. 30% weight reduction (compared to normal weight concrete and ceramic bricks with vertical holes) is achieved. Thus the earthquake forces that affect the structure are reduced and costs related to building materials, transport and manipulation drop and diminish the* CO_2 *– emissions. The use of multi-role materials is encouraged: lightweight concrete and autoclaved aerated concrete AAC join structural and thermal insulation properties, AAC blocks act also as formwork for the concrete columns. The following aspects are investigated: (i) suitability of lightweight concrete for ductile beams and frame nodal regions; (ii) seismic behaviour of concrete columns cast within AAC blocks; (iii) seismic behaviour of decoupling system for partition walls; (iv) rigid diaphragm behaviour of lightweight concrete slabs; (v) accuracy of innovative rotational sensors network.*

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1. General considerations

The seismic performance of a lightweight structure built of innovative materials is investigated by shaking table tests. Multi-role materials join together in an attempt of creating for seismic areas an efficient building from structural, energy-household and CO_2 emissions point of view. Lightweight concrete for slabs and beams exchange normal weight concrete and autoclaved aerated concrete (AAC) blocks (Michelini et al., 2023) build external and partition walls instead of ceramic bricks with vertical holes. A 30% weight reduction is achieved and thus design seismic forces are reduced. Costs related to building materials, transport and manipulation drop and diminish the CO_2 – emissions.

Lightweight concrete and AAC blocks have structural as well as thermal insulation properties. AAC corner blocks for external walls act also as formwork for RC columns.

A shaking table test procedure was chosen because of the specimen plan irregularity. Both stiffness and live load distribution are uneven and produce torsional effects. Especially the rigid diaphragm behaviour of lightweight concrete slabs will be investigated.

The project partners are described in section 2. The specimen geometry and special material properties are presented in section 3. The CEA test facility is described in section 4 together with the rotational movement sensors. Challenges passed during the specimen design and the main expected project outcomes are indicated in section 5.

2. Project partners

The Technical University of Bucharest (UTCB) is represented by the User Group Leader Dietlinde Köber. She is lecturer and researcher at the Technical University of Bucharest since 2005. She has a broad scientific knowledge in earthquake resistant design (Köber et al 2022, Constantinescu et al 2015, Köber & Zahn 2015, Constantinescu & Köber 2015), and carried out extensive research on the nonlinear behavior of plan irregular structures (Köber 2020, Köber & Zamfirescu 2013, Köber et al 2022, Köber & Zamfirescu 2016). She is member of the scientific committee of EAEE Working Group 8 on Irregular and Complex Civil Structures and gained practical experience as designer, verifying engineer and energy building auditor. Ms Köber co-authored the current version of the Romanian Seismic Design Code for Existing Structures (P100-3/2019) and was involved in 2006 in the editing process of the Romanian Seismic Design Code, (P100-1/2013). Furthermore, she was assistant manager in the COSCEF project POSCCE-A2-O2.2.1-2013-1 on the University laboratory infrastructure extension and part of the research team for the test campaign TRAROM, PN-III-P2-2.1-PED-2016-1073, on the revival of Romanian traditional houses.

Christoph Butenweg is representing the Center for Wind and Earthquake Engineering (CWE) at RWTH Aachen University. Through the involved institutes the CWE offers an excellent and long-standing expertise in structural dynamics and runs comprehensive efficient and highly specialized testing facilities. He gathered extensive experiences in experimental testing and numerical modelling within the framework of European projects (Insysme - ID 606220-FP7, Euroseis-Risk - EVG1-CT-2001-00040, Safefloor - ID: EVK4-CT-2000-00020), in projects with industrial partners (Halfen AG, Bayer AG, BASF, Allianz) and in research projects supported by the German Science Foundation, all of them dealing with structural dynamics and earthquake engineering. His research aims at developing and improving seismic design methodologies for RC and URM structures, as well as industrial facilities. He has undertaken large- to full-scale test programmes (SERA – SPIF) and is a versatile user of numerical modelling techniques in seismic engineering. Furthermore, he is highly involved in the code development on national and European level (Leader PT5 and member of the management group SC8). Relevant publications for the proposal with respect to the seismic design of masonry structures are (Butenweg et al 2019, Butenweg & Marinkovic 2019, Morandi et al 2022). He will support the proposed project with his experience from former test campaigns and the design and detailing of the test structure.

Holcim Group is 70,000 people around the world who are passionate about building progress for people and the planet. As a global leader in innovative and sustainable building solutions, Holcim is enabling greener cities, smarter infrastructure and improving living standards around the world (Environmental Product Declaration and Strategy 2025 – Accelerating Green Growth). The proposed project is in line with the global company development on innovative and sustainable concrete receipts, promoting lightweight concrete with pumice aggregates, LCPA (Kaffetzakis & Papanicolaou 2016). Within the proposed project Holcim Group is represented by Vasileios Kaloidas, senior researcher and Maria Nomikou from Holcim Greece and Marius Dumitrescu from Holcim Romania. They develop research activities on the behavior of structural concrete with pumice aggregates and support the project team with respect to the concrete receipt, cast procedure and post seismic damage interpretation for concrete elements (Papanicolaou & Kaffetzakis 2011). Furthermore Holcim Group will provide the concrete for the test specimen. Former analytical research projects were developed with UTCB on the structural and environmental advantages of lightweight or high strength concrete solutions in earthquake resistant buildings (Marius Dumitrescu, Holcim Group Romania).

With over 5300 employees, the Xella Group is one of the leading, internationally active solution providers of building and insulation materials. Xella is one of the world's largest manufacturers of AAC and calcium silicate blocks, headquartered in Duisburg and has 78 plants and sales organizations in 22 countries. Within the proposed project Xella is represented by Xella Technologie- und Forschungsgesellschaft mbH (XTF) that shapes the future of AAC with systematic innovation, in-depth research, and technological developments: for clever solutions, new benchmarks, and long-term satisfied customers. XTF brings together technical experts with an experienced research team to jointly develop future-proof solutions for sustainable construction and renovation. XTF has excellent experimental facilities and a long-standing experience in material testing and research on seismic safety of masonry (Schoch et al. 2018, Miccoli 2018, Miccoli 2020). Within the proposed project Xella is represented by Dr. Lorenzo Miccoli, project leader at XTF. He is well qualified to join the project with his expertise in planning, testing and design of AAC masonry structures. Furthermore, Xella will provide the required products for the test specimen.

GEOM, the Geophysical Observatory from the Ludwig-Maximilian-Universität München, Germany has a 74 years expertise in geomagnetic observations. Within the framework of the GIOTTO project (funded by the German Federal Ministry for Education and Research, BMBF) GEOM developed the first of its kind 6C sensor network for building health monitoring (Wassermann et al 2022, Bernauer et al 2021). This sensor network consists of 14 inertial measurement units that were adapted for the needs of seismic building health monitoring. It will be available for the proposed project. The responsible person within the proposed project is Felix Bernauer, postdoctoral researcher at GEOM. He will support the project by monitoring the 6C sensor network installed to observe six degrees of freedom of motion within the test specimen (without external reference), correct translational acceleration recordings for dynamic tilt and directly measure harmful building torsional modes.

EMPA, the Swiss Federal Laboratories for Materials Science and Technology, conducts cutting-edge materials and technology research. Empa’s R&D activities focus on meeting the requirements of industry and the needs of society, and thus link applications-oriented research to the practical implementation of new ideas. Within the proposed project EMPA is represented by the Structural Engineering Lab, which develops in collaboration with national and international universities, research institutes and industrial partners new solutions in the fields of structural strengthening and structural dynamics with the goal to improve the safety, serviceability and durability of civil structures. The laboratory is equipped with a large testing hall and several unique testing machines, has skilled personnel with a vast experience in performing dynamic tests and provides the industry with high level services. The responsible person within the proposed project is Dr. Christoph Czaderski, senior researcher at EMPA. He will support the project with his expertise in testing and strengthening of concrete structures.

3. Specimen characteristics

3.1. Geometry

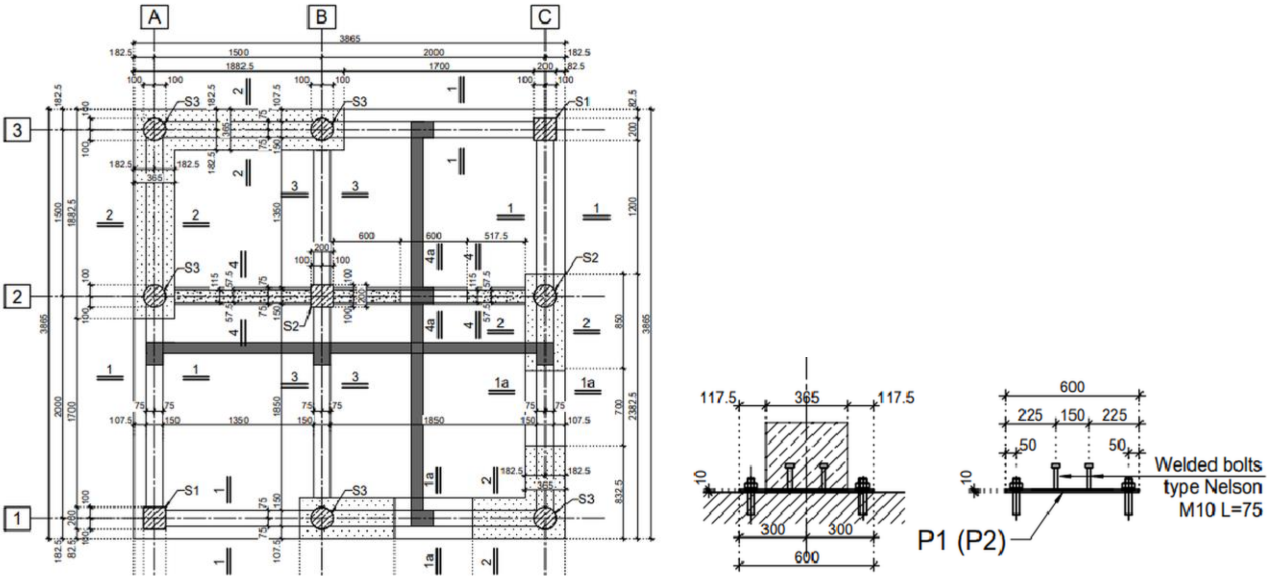
The specimen plan layout was chosen to fit the shaking table dimensions and the position of the anchorage points in the shaking table plate, in order to fix the specimen. Therefore a 3.865 m × 3.865 m square plan layout was chosen. The specimen has two levels of 2.5 m each.

The plan layout of the ground floor is shown in Figure 1a. Plan irregularity is created by the corner position of the external walls, by the uneven spans and by the live load distribution on the slabs.

15 × 20 cm beams support 10cm slabs. Two different lightweight concrete classes were chosen for the two slabs: LC 25/28 for the ground floor and LC 20/22 for the first floor. Beams are supported by 20 × 20cm square or diameter 20cm circular columns. The circular columns are cast in holes from the extenal walls

AAC corner blocks (Figure 2a). Columns are built of normal weight concrete C20/25. Reinforcement BSt500B will be used.

The specimen is supported by foundation beams placed in each span. The foundation beams are connected to a 15mm steel base plate by the help of connectors (Figure 1b). The steel base plate acts as bottom formwork for the foundation beams. It also allows the specimen fixation to the shaking table.



a) b)

Figure 1. a) Plan layout ground floor; b) Section through foundation beam

The partition walls are placed in axis 2 at ground floor and in axis B at the first floor. In each level, one span has a door opening and the other one is a wall without openings. The partition walls are decoupled at the top by use of Regupol decoupling elements (Figure 2b). The decoupling element is fixed at the bottom of the upper beam, then the partition wall is built below the decoupling element. Finally, expansion mortar Quellmörtel QM 120 is filled from both sides of the decoupling element.

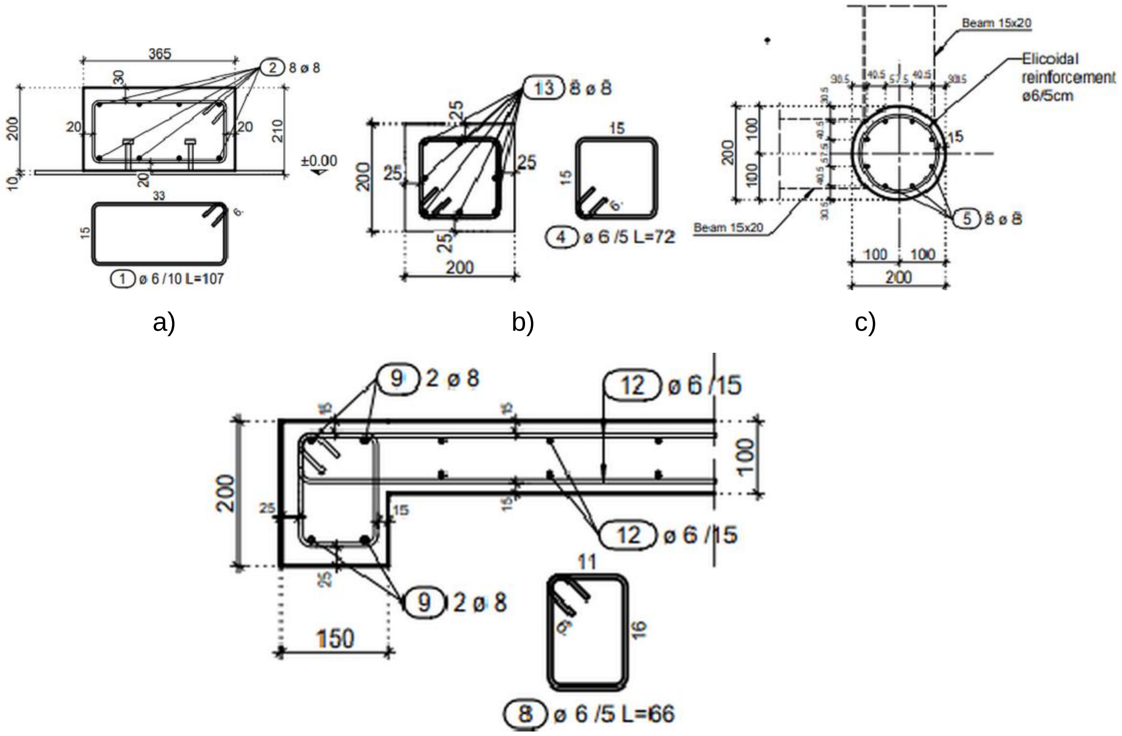
a) b)

Figure 2. a) AAC blocks for exterior walls, with holes at their ends; b) Regupol decoupling element for partition walls

Typical reinforcement details are shown in Figure 3. Longitudinal bars and stirrups are provided for beams and rectangular columns. The vertical bars are surrounded by spiral reinforcement for the circular columns. Bars with a diameter of 8 mm are used for the longitudinal reinforcement of beams and columns. Bars with a diameter of 6 mm are used for the longitudinal slab reinforcement and for the transversal reinforcement of beams and columns.

Capacity design requirements were applied for design, following the strong column-weak beam principle.

Reinforcement detailing was performed according to the high ductility class provisions.



a) b) c)

d)

Figure 3. Reinforcement detailing: a) Foundation beam; b) Square column; c) Circular column; d) beam and slab

3.2. Material properties

Lightweight concrete with pumice aggregates is a modern building material provided by Holcim Greece. It joins structural as well as thermal insulating properties and reduces the overall building weight and thus the expected seismic forces. It is available as mixed design receipt. A premix is not possible due to the pumice humidity sensitivity.

In order to obtain structural lightweight concrete, a higher cement consumption than for normal weight concrete of equal class is needed, which increases the CO_2 emission. Nevertheless the reduced self-weight drops transport and manipulation costs and concrete volumes for structural elements. The thermal insulation properties of lightweight concrete reduce costs with thermal isolation materials.

Additionally, in order to compensate for the increase in CO2, a cement with a low carbon footprint was used - EcoPlanet Plus - II/BM(V-LL)42,5R (Holcim România, 2023) for the preparation of the normal weight concrete used in columns. (30% lower CO2 compared to conventional cement - CEM I EU 27, according GNR PROJECT Reporting CO2, 2020).

Table 1 compares concrete characteristics from lightweight concrete to concrete class C20/25.

Table 1. Lightweight concrete characteristics as percentage of concrete class C20/25 characteristics

Concrete class	**Self weight**	**Secant elastic modulus**	**Ultimate strain**	**Tension strength**	**Cement amount**	**Thermal conductivity**
LC 25/28	72%	67%	89%	89%	147%	40%
LC 20/22	60%	40,5%	81%	81%	140%	40%

AAC blocks for external walls / partition walls have the following dimensions (length/thickness/height): 599 × 365 × 249 / 599 × 115 × 249. They are joined by thin-layer mortar. Table 2 summarizes some AAC material characteristics.

Table 2. Characteristics of AAC masonry components

Material	**Bulk density** *kg/m^3*	**Compressive strength** *MPa*	**Thermal conductivity** *W/mK*
AAC block external wall	305-350	> 2.6	0.07
AAC block partition wall	505-550	>4.6	0.14
thin-layer mortar	≥ 1300	>10.0	not relevant

Figure 4 shows the elevation of external wall placed in axis 1. Ground floor door opening is provided with a prefabricated lintel, according to usual masonry works. In the upper story no lintel was introduced, in order to check differences in the AAC wall behaviour with/without lintel. In self-built houses practice, especially due to economical reasons beams take over the lintel role.

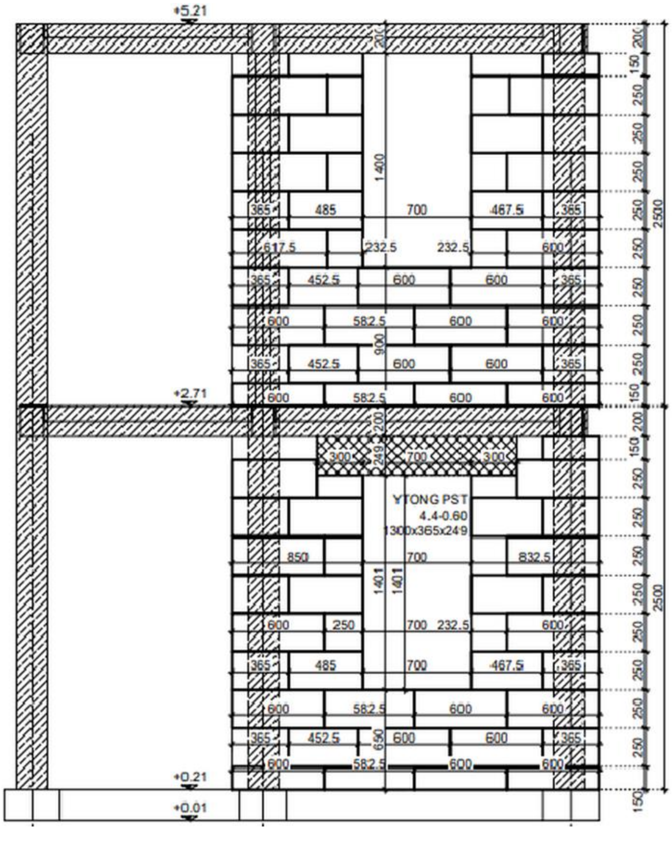


Figure 4. External AAC wall elevation, axis 1

4. Laboratory facility

The TAMARIS infrastructure and its main shaking table AZALEE, to which access is offered, belong to CEA's Seismic Mechanics Study Laboratory (EMSI), who is leading the French SEISM Institute (www. https://www.institut-seism.fr/), is part of the Université Paris-Saclay regrouping about 19 academic partners and research institutes, and has international RTD collaborations with other facilities (EU, Japan, China, USA). The AZALEE shaking table, with 100t allowable maximum model mass, is one of the largest shaking tables in Europe. To date, tests with masses up to 92t have been successfully performed. The shaking table is 6mx6m and 6 Degrees-of-Freedom (DoF), allowing testing specimens under independent excitations of various types: sinusoidal, random, shock and time-history with 0.7 to 50 Hz frequency ranges. Maximum accelerations of 1g and 2g in the horizontal and vertical directions, respectively, can be applied to specimens with the maximum payload of the table. The peak velocity of the shaking table is 1m/s, peak displacements are 0.125 m and 0.1 m in the horizontal and vertical directions, respectively (https://sera-ta.eucentre.it/ta-facilities/ta_f04_cea/).

Services currently offered by the infrastructure: The services offered to users that make the infrastructure unique include a team of about 20 expert scientists and technicians working in earthquake engineering RTD projects, a high quality control and acquisition system allowing recording 256 channels, and a scientific computing and processing system (CAST3M) for the definition and execution of tests and subsequent interpretation of results (https://sera-ta.eucentre.it/ta-facilities/ta_f04_cea/).

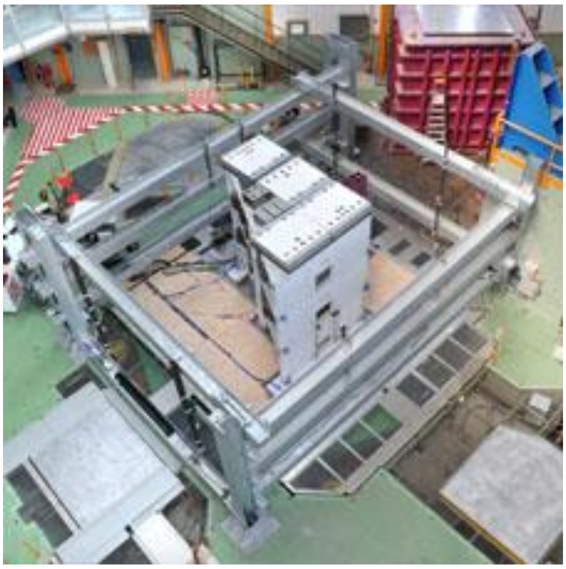


Figure 5. AZALEE shaking table, https://sera-ta.eucentre.it/ta-facilities/ta_f04_cea/

As the specimen represents a plan irregular structure, torsional movements are expected under seismic action. The rotational movement of both slabs will be measured once with classic instrumentation (translations of slab edges) and once with the innovative 6C sensors. The sensors rely on a IMU50 unit produced by Exail France. The communication and data interface as well as the housing were modified by GEOM to fit the needs of seismology, Figure 6.

Figure 6. 6C sensor for building health monitoring

5. Challenges during specimen design phase

During the design phase of the specimen several challenges appeared. The main ones and their solutions are presented hereinafter:

- Specimen build-up aside from the shaking table
  Due to concrete works and the need of protecting the shaking table, the specimen will be built nearby to the shaking table and lifted on the shaking table for fixing, instrumentation and testing phases.
  Several lifting procedures were investigated: lifting from the bottom, the top or beneath the first story.
  The best procedure was found to be lifting beneath the first story, by inserting HEA 100 steel profiles under the beams over the first story.
  Lifting from the top of the specimen would produce high stresses in the central column and in the beams (as the lifting points are the four plan layout corners).
  Lifting from the bottom would be best for the specimen but would imply a more complex foundation system and higher specimen weight (see next challenge).
  Stresses and deformations were checked for the lifting phase. According to the specimen model, concrete cracking should be reached during lifting.
- Specimen weight limitation due to crane capacity
  The crane capacity that serves the shaking table area is of 25 tons. As the specimen cannot be erected partially and mounted on the shaking table (due to the AAC external walls that act also as framework for some concrete columns), the overall specimen plan layout had to be reduced from 4.65 × 4.65 m to 3,865 × 3,865 m. The struggle was to keep up with realistic spans for 20cm high beam sections. The story heights were not reduced in order to have realistic dimensions for the AAC wall panels. Erection of partition walls will be done on the shaking table after lifting because it would be difficult to assure the partition walls stability during lifting and in this way a specimen self weight reduction could be achieved for the lifting phase.
- Layout of additional load panels on the slabs to model live loads and maximize torsional effects. Loads on the slab over the ground floor needed to be small enough to be handled by people, as the crane doesn’t reach inside the specimen.
- Steel lifting frame existing in the laboratory needed to be checked for the specimen. Components used for supporting the slab of a specimen from a previous project will not be used as the lifting occurs by supporting two 1st story beams. I this way the lifting device becomes lighter and weight for the specimen is gained (in order to not overcome the 25 tons limit of the crane).

6. Expected outcome

The following aspects are investigated within the test campaign:

- Suitability of lightweight concrete for ductile beams and frame nodal regions;
- Seismic behaviour of concrete columns cast within AAC blocks;
- Seismic behaviour of decoupling system for partition walls;
- Rigid diaphragm behaviour of lightweight concrete slabs;
- Accuracy of innovative rotational sensors network.

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