Assessment of the Capacity for Reinforced Concrete Elements Cast in Insulating Forms

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***Abstract*—Under the current conditions of construction that consume as little energy as possible, new technologies have been developed both for the production of renewable energy and for the implementation of high performance materials that efficiently isolate the interior spaces of the buildings. Structures with reinforced concrete walls can be made using insulating concrete forms that meet the requirements for a passive house. The fact that fresh concrete is casted into these forms that remain throughout the construction lifetime, allows a more efficient hydration of cement, which increases the strength of reinforced concrete. Using the results of laboratory tests, this paper presents a numerical analysis of different types of reinforced concrete walls, comparing the resistance capacity and the ductility for both cases: concrete casted in normal forms and using insulating concrete forms.**

***Index Terms*—passive house, strength, ductility, normalized axial force, mechanical reinforcement ratio.**

I. Introduction

Lately, a great emphasis has been placed on buildings that consume a very small amount of energy, which leads to the adoption of special thermal insulation measures for buildings in cold and temperate areas.

Passive House is a quickly emerging standard that requires buildings to use an extremely small amount of energy for their heating and cooling needs. Passive Houses are very well-insulated and virtually airtight. Compared to traditional constructions, for the passive ones an investment of approximately 15% is needed, but the energy consumption is over 80% lower. This method of construction was first developed in Germany and has since spread throughout Europe and North America; gradually improved, the method has the potential to dramatically reduce society's energy consumption, and therefore radically reduce our carbon emissions.

In terms of energy consumption, the criteria that a passive house has to achieve are [1,2]:

- to have an annual heating and cooling demand of not more than 15 kWh/m^2 per year in heating or cooling energy (compared to 100-200 kWh/m^2 per year for a classic building) or to be designed with a peak heat load of 10 W/m^2;
- total primary energy (source energy for electricity, etc.) consumption (primary energy for heating, hot water and electricity) must not be more than 60 kWh/m^2 per year;
- the building must not leak more air than 0.6 times the house volume per hour at 50 Pa as tested by a blower door.

A passive house is usually equipped with modern systems that produce green energy: photovoltaic panels, heat pumps (earth-air heat exchange), but also efficient components that help to isolate it: triple glazed windows with low-emissivity coatings, thick exterior thermal insulation [3].

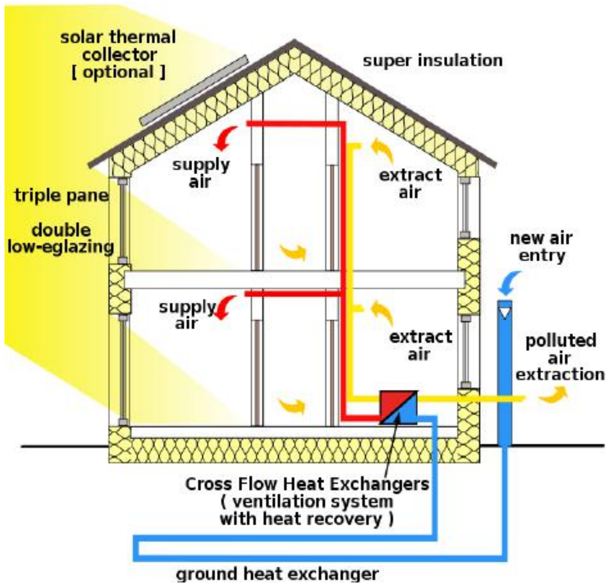

Figure 1. Passive house scheme [4]

Regarding the actual materials as thermal insulation, mineral wool, polyurethane foam, natural cork, plain expanded polystyrene, extruded polystyrene and graphite polystyrene are used. The thermal efficiency of a material is defined by the thermal conductivity coefficient. The lower the thermal conductivity coefficient of a material, the better it is thermal insulation. For example, the value of the thermal conductivity coefficient for extruded polystyrene is 0.035 W/mK. The thickness of the thermal insulation layer is recommended to exceed 10 cm in order to reach the requests of a passive house.

A solution in this sense is the realization of reinforced concrete structures with walls casted in modular forms made of heat insulating materials (e.g. graphite polystyrene).

Constructions made using modular thermo-insulating forms are beneficial to the environment due to reduced operating energy, reduced CO_2 emissions, increased lifespan, and the use of local and recycled materials.

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Along with the advantage of thermal propriety and low CO_2 emissions, this solution allows fresh concrete to hydrate for a longer period of time and consequently to reach higher resistances than under normal casting conditions.

When Portland cement is mixed with water, a chemical reaction called hydration takes place. The extent to which this reaction is completed influences the strength and durability of the concrete. Freshly mixed concrete normally contains more water than is required for hydration of the cement; however, excessive loss of water by evaporation can delay or prevent adequate hydration. The surface is particularly susceptible to insufficient hydration because it dries first. If temperatures are favorable, hydration is relatively rapid the first few days after concrete is placed; however, it is important for water to be retained in the concrete during this period, that is, for evaporation to be prevented or substantially reduced.

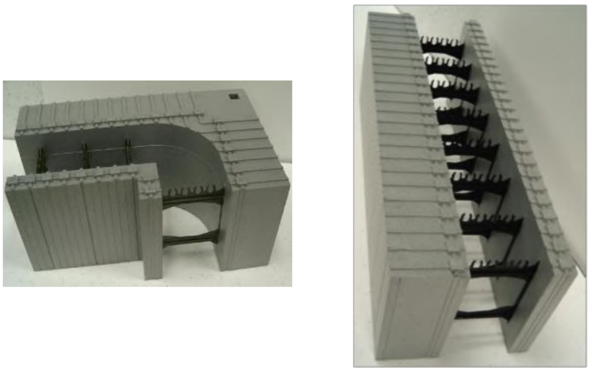


Figure 2. Types of modular insulation concrete forms

With proper curing, concrete becomes stronger, more impermeable, and more resistant to stress, abrasion, and freezing and thawing. The improvement is rapid at early ages but continues more slowly thereafter for an indefinite period. Fig. 2 shows the strength gain of concrete with age for different moist curing periods. [5]

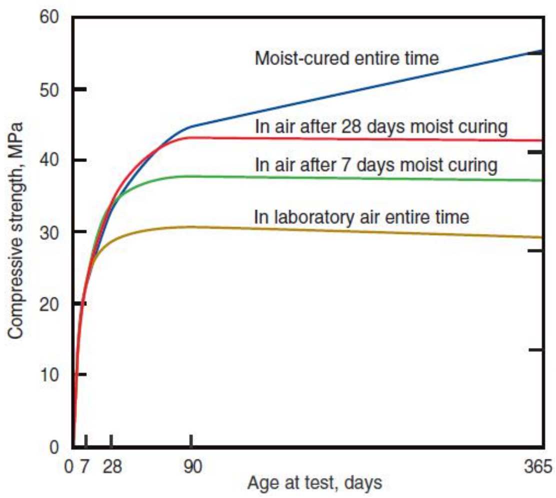


Figure 3. Effect of moist curing time on strength gain of concrete [5]

As it is noticed, the concrete moist-cured entire time developed higher compressive strength. After the casting process, normal formworks are kept in place for molding between 14 and 28 days, and then they are removed. On the other hand, the modular thermo-insulating forms remains throughout the construction lifetime and keep the water from evaporating, increasing the compressive strength of the concrete and thus the strength capacity of the structural elements.

II. Structural Configuration

Using modular thermo-insulating forms, both interior and exterior reinforced concrete walls are easily generated. The reinforcement is placed horizontally and vertically, creating a net on each side of the wall.

The intersection of reinforced concrete walls must be treated with great care because, in case of lateral loads due to seismic actions, these areas become stress concentrations. Thus, the intersections must be strongly reinforced, both with larger diameter vertical bars and with stirrups distributed throughout entire height. The correct arrangement of the reinforcement, with minimum percentages, minimum diameters or maximum rebar distances is normalized [6].

The corners are rounded outwards for a more efficient behavior in tensions distribution.

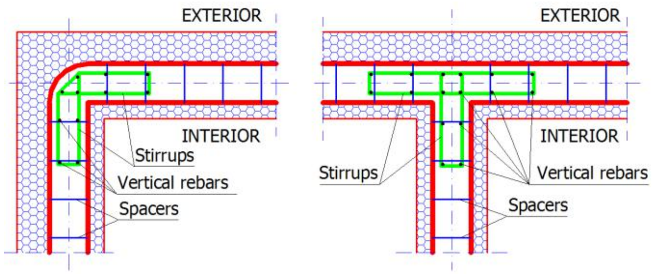


Figure 4. Intersection details for reinforced concrete walls

The walls thus obtained can be easily finished with different materials (wood, stone, brick, cardboard plaster, paneling, etc.), which can be attached to the formwork using nails or screws. Formwork systems are designed and built in such a way that horizontal and vertical grooves can easily be cut into the polystyrene layer to mount the electrical cables and pipes of the sanitary installation.

At the intersection between floors and structural walls, in case of using modular thermo-insulating forms, it is recommended to generate beams, with additional longitudinal rebars and stirrups.

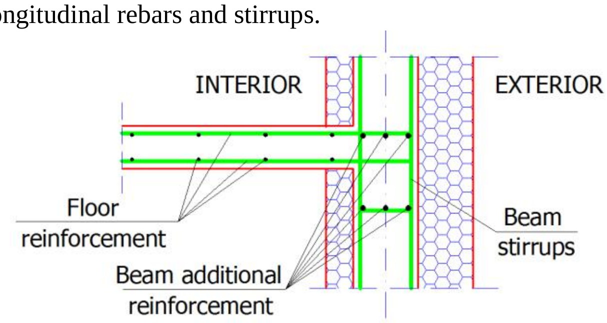


Figure 5. Detail of floor-wall intersection

III. Laboratory Test and Results

Experimental test was performed to compare the compressive strength of the concrete casted in polystyrene moldings with compressive strength of concrete casted in traditional wooden formwork, in similar conditions as in any construction site. Thus, normal conditions (humidity, temperature, atmospheric pressure) were reproduced in the laboratory.

In the experiment, 24 casting forms were manufactured with 15×15×15 cm^3 size, as follows: 12 polystyrene forms, 12 wooden forms. Concrete prepared according to the recipe C20 / 25 class was cast in these forms.

Concrete cast in wood forms was de-molded after 7 days and the compressive strength was determined at 7, 14, 28 and 90 days, whereas concrete cast in polystyrene forms was de-molded just before the compressive test.

Sampling, storage and testing have been performed by an ISC Authorized Testing Laboratory, in accordance with the current standards [7-9].

Figure 6. Testing the concrete specimens

The compression tests on the specimens were performed after 4 sampling time intervals: 7, 14, 28 and 90 days. At each term, three specimens of each type were subjected to compression:

- specimens cast in wooden forms and kept under conditions that comply with [8];
- specimens cast in wooden polystyrene forms.

The values obtained for the compressive strength, depending on the duration of storing and on the type of casting form, are shown in Table I.

TABLE I. COMPRESSIVE STRENGTH FOR CONCRETE SPECIMENS [N/MM^2]

Type of concrete forms	Storing interval [days]	Sample 1	Sample 2	Sample 3	Average values
Polystyrene forms	7	20.00	18.60	20.00	**19.55**
	14	23.11	21.77	24.00	**22.96**
	28	27.55	26.66	28.44	**27.55**
	90	30.66	30.66	30.00	**30.44**
Wooden forms	7	17.77	16.66	18.88	**17.77**
	14	22.22	21.33	21.77	**21.77**
	28	25.77	26.66	26.22	**26.22**
	90	27.11	26.66	28.00	**27.36**

In order to better illustrate the difference of concrete compressive values stored in the two formwork variants, a suggestive graph representation was made (Fig. 7).

As it is easily noticed, the differences between these values increase with the storing intervals. For example, if the difference is only 1.33 MPa (4.8%) after 28 days - the interval that gives the class of the concrete, after 90 days the difference increases to 3.08 MPa (10.11%). On the other hand, the results confirm the theory and other tests developed in this domain (see the similarity between Fig. 3 and Fig. 7).

This phenomenon is explained by the mineral composition of the cement, the hydraulic binder within the concrete. The four cement minerals (C_3S - Tricalcium Silicate, C_2S - Dicalcium Silicate, C_3A - Tricalcium Aluminate and C_4AF - Tetracalcium Aluminoferrite) play very different roles in the hydration process that converts the dry cement into hardened cement paste.

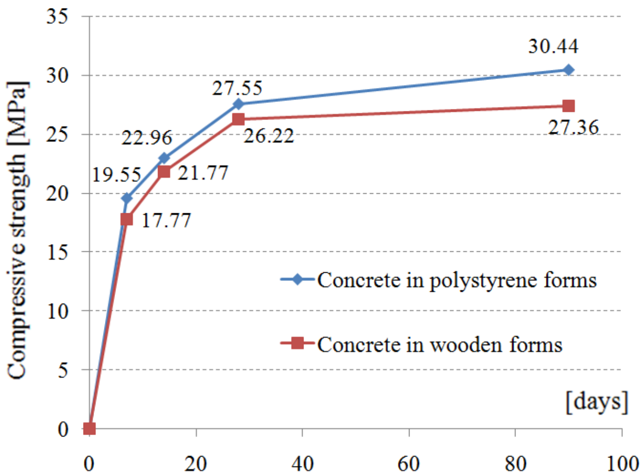


Figure 7. Values of compressive strength for concrete specimens tested after different storing intervals

The hydration of C_3S gives cement paste most of its strength, particularly at early times. C_2S is much less soluble than C_3S, so the rate of hydration is much slower; furthermore, C_2S hydration contributes little to the early strength of cement, but makes substantial contributions to the strength of mature cement paste and concrete. C_3A is highly soluble, even more than C_3S, and along with C_4AF contribute little to the strength or other engineering properties of cement paste. In conclusion, the longer presence of water in the concrete mix allows further chemical reactions (hydration) of the cement component C_2S, having as a result the increasing of the concrete compressive strength.

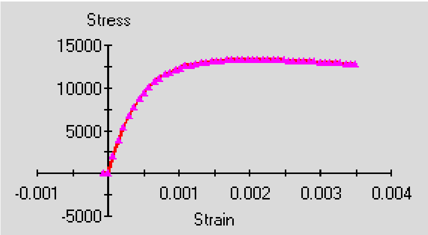
Starting from the different values of the compressive strength after 90 days for both tested cases (using samples stored in wooden versus polystyrene forms), a numerical analysis was set up, in order to determine the influence of this difference on the capacity (strength and ductility) of reinforced concrete elements.

IV. NUMERICAL ANALYSIS

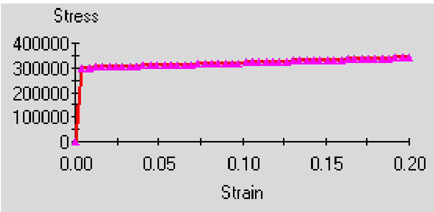
The analysis is developed using XTRACT computing program, designed to determine the strength and ductility of reinforced concrete elements, considering the non-linear behavior for components (concrete and steel). A complete analysis offers reliable data regarding the maximum strength, the ductility coefficient of wall cross-section, the location where the material firstly crushes, taking into consideration post-elastic behavior of concrete and steel.

For present numerical analysis, following simplifying assumptions were used:

- Bernoulli's assumption: plane sections remain plane during charging and any section of a linear element (beam, column) that was perpendicular to the neutral axis before the beam deforms will remain perpendicular to the neutral axis after the element deforms;
- the concrete is considered unconfined;
- the concrete-reinforcement bond is perfect;
- the constitutive laws (uniaxial stress-strain relationship) for component materials are defined as follow: for concrete all the behavior stages are controlled (yield, crushing, spalling, failure), whereas for steel a simplified bilinear behavior is adopted (Fig. 8).



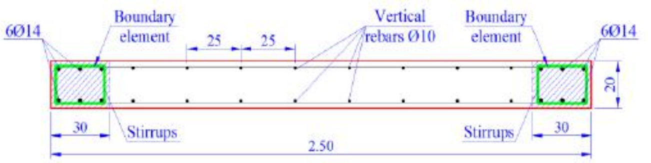
a) concrete



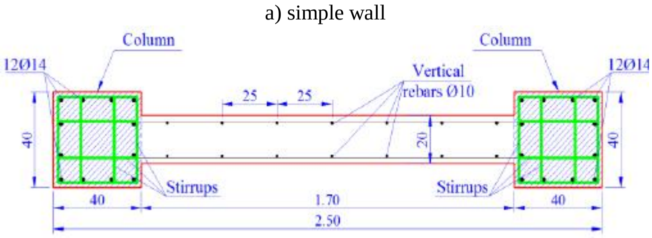
b) steel

Figure 8. Constitutive laws for component materials of reinforced concrete element

Taking into consideration that the most common vertical reinforced concrete elements cast in insulating forms are the walls, two different types of these structural elements are considered: a simple wall (with rectangular cross-section) and an I-shape wall (with columns at the extremities), Fig. 9.



a) simple wall



b) I-shape wall

Figure 9. Types of concrete walls and reinforcement details

According to the design code [6], the extremities of the wall (boundary elements), where combined seismic and gravity loading results in high compressive demands on the edge, must be strengthened by longitudinal and transverse reinforcement. Closely spaced transverse reinforcement (stirrups) encloses the vertical boundary bars to increase compressive strain capacity of core concrete and to restrain longitudinal bar buckling.

The values of the mechanical reinforcement ratio for vertical rebars in the boundary elements, ω_v, must not exceed the value 0.15 [6], considering that the building is located in a seismic area (terrain acceleration $a_g > 0.15$ g) where the ductility requirements are more severe. The mechanical reinforcement ratio is calculated with the next formula:

$$\omega_v = \frac{A_{sv}}{A_c} \cdot \frac{f_{yd}}{f_{cd}}, \qquad (1)$$

where A_{sv} is the cross-sectional area of vertical reinforcement in the boundary element; A_c is the cross-sectional area of the boundary element; f_{yd} is the design value for yield strength of the reinforcement steel; f_{cd} is design value for concrete compressive strength.

The computing analysis is referring to:

- the ductility capacity of the walls, bending moment - curvature graphs being generated;
- the strength capacity in terms of determining ultimate bending moments, the yield moments (value of the bending moment when the reinforcement start to yield), P-M interaction graph and capacity orbit for the wall sections.

A. *Ductility capacity*

For the simple shape walls, the bending moment - curvature graphs resulted almost similar, except for the final part, where small differences occur (Fig. 10). Nevertheless, the value of the curvature ductility is 9.905 for the case of polystyrene forms, whereas the value for the same coefficient in case when wooden forms are used is 8.98; the difference of the curvature ductility represents 10.3%.

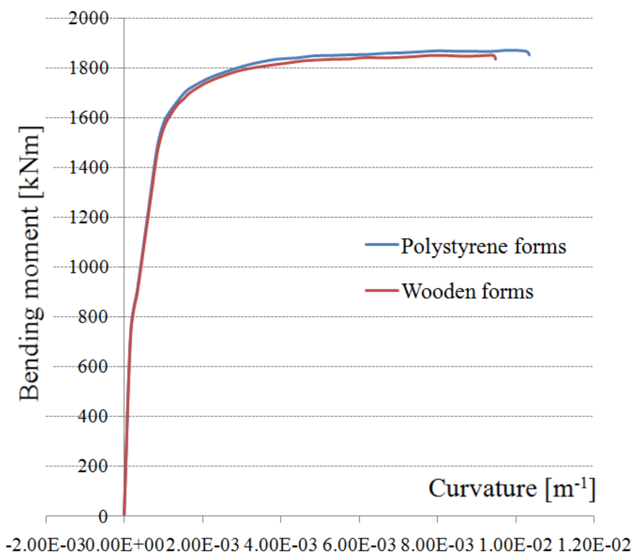


Figure 10. Bending moment - curvature relation

For the I-shape walls, the aspect of the graph moment-curvature is the same as in Fig.10, with the values for curvature ductility: 15.51 – polystyrene forms case, 14.24 – wooden forms case. The difference between these values is 8.9%. On the other hand, increasing the boundary elements area along with more vertical reinforcement determine an obvious increase of curvature ductility of I-shape walls towards simple shape walls.

The mode of failure is the same for all types of wall: crushing of the compressed concrete, after the reinforcement reaches its yield stress. The collapse of the reinforced concrete walls is due to the material failure. To overcome this, the walls should have sufficient cross-sectional area and reinforcement, so that the stress remains always under the specified limit.

B. Strength capacity

For the simple shape walls, the ultimate moment is 1852 kN·m for polystyrene forms case and 1836 kN·m for wooden forms case (only a 0.87% difference). In the same manner, the values for ultimate moments are very close for I-shape walls: 2474 kN·m - polystyrene forms case; 2453 kN·m - wooden forms case. A graph representing capacity orbit for the I-shape wall sections is shown Fig. 11. Again, the values of the ultimate moments are higher for the I-shape walls towards simple shape walls. I-shape walls are more ductile and more resistant to seismic and gravity loading than the simple plane walls.

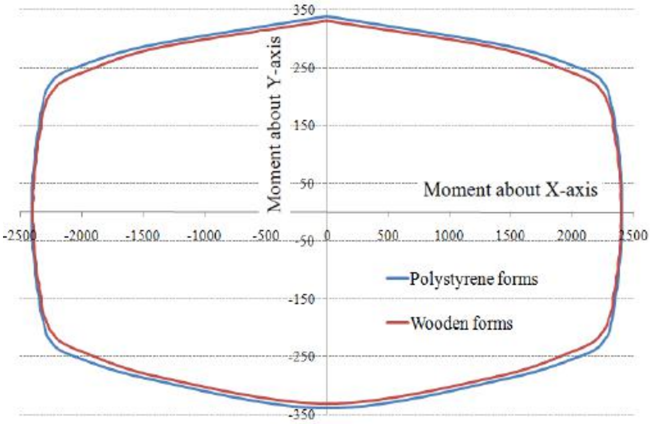


Figure 11. Capacity orbit diagram

The above diagrams (Fig. 10 and Fig. 11) are plotted for an axial force of 700 kN, representing a 5% normalized axial force, as the walls are part of a multi-storey building. The normalized axial force is calculated with the formula:

$$v = \frac{N}{A_{tc}} \cdot \frac{1}{f_{cd}}, \tag{2}$$

where N is axial force; A_{tc} is the total cross-section area of reinforced concrete wall; f_{cd} is defined above.

An interesting result refers to the P-M interaction graph, where the capacity of the section is analyzed in terms of axial force versus bending moment relation. As it is shown in Fig. 12, the graph is the same for those two cases at the lower part and for the higher part, graphics are splitting and have different traces. Even for simple or I-shape forms, the behavior is the same, with the cross-section strength increasing with concrete compressive strength only when axial force becomes important (the value of normalized axial force exceeds 20%).

If the wall was loaded only with axial force at maximum capacity (bending moment is zero), the higher value of compressive strength for the concrete casted in insulating forms determines a better capacity: 14260 kN, compared to 12990 kN when normal wooden molds are used (an important difference of 9.77%) for I-shape walls (Fig. 12) and 10780 kN compared to 9800 kN (10% difference) for simple shape walls.

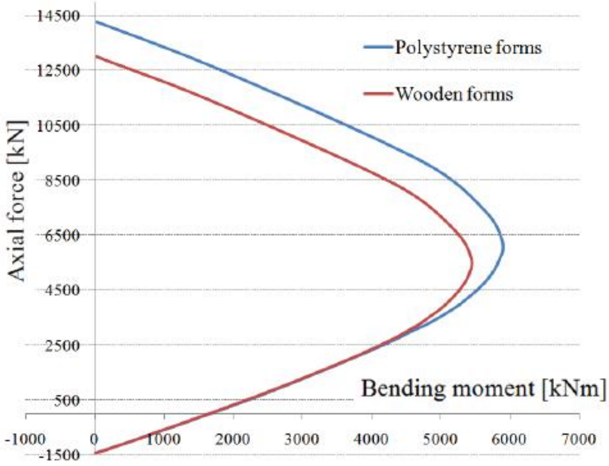


Figure 12. P-M interaction for reinforced concrete walls

V. CONCLUSION

The purpose of this study was to determine whether the storing of the fresh concrete in insulating forms has an important influence on the compressive strength of concrete and furthermore whether the structural elements casted using this technology possess better ductility and strength capacity.

Tests in laboratory demonstrate that good hydration of cement due to keeping the water longer in the concrete cast in insulating forms lead to higher values for compressive strength after 90 day storage - about 10%. We also propose a test on samples stored for a longer period, to observe the increase in the gap.

The numerical analysis considered the non-linear behavior for components (concrete and steel). Two types of wall were analyzed: a simple plane wall and an I-shape wall, with different boundary elements, both with values of concrete compressive strength obtained from the tests in the lab (for polystyrene forms and for wooden forms).

The results of the analysis reveal important aspects regarding the behavior of reinforced concrete walls under seismic and gravity loadings.

For higher value of concrete compressive strength, the ductility capacity of a structural element increases due to the higher value of the ultimate curvature. The element becomes more ductile, having a higher capacity to deform and to absorb more energy during deformation process.

Conformation of boundary elements is very important in terms of ductility and strength capacity: the bigger the area of boundary element and the values of the mechanical reinforcement ratio are, the higher are the ductility and the strength capacity. Ductility capacity increases with more than 55% for I-shape walls compared to the simple plan walls, whereas the strength capacity increases with 33%.

For reduced value of axial force (normalized axial force less than 20%), the influence of concrete strength is insignificant; on contrary, for walls with important axial compression force, choosing the adequate concrete class becomes decisive for increasing the strength and for a better behavior. The normalized axial force used for analysis was around 5% and the ultimate moments have close values for those two cases (concrete cast in polystyrene forms and using wooden forms).

To conclude, the influence of the concrete cast in insulated forms on concrete compressive strength is significant, having as consequences better ductility and strength capacity for component elements of reinforced concrete structures.

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