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# An Experimental and Numerical Study of the Effect of Heat and Thermal Shock in Precast Concrete Wall System

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**Abstract.** *The aim of the paper is to analyse the performance of a precast concrete wall system under heat and thermal shock (physical phenomena). The understanding of thermal shocks in building systems is a challenge because of the requirements and complexities of the phenomena behaviour through cycles of heating and cooling provided by the environment (sun followed by suddenly rain). The period of duration of the phenomenal during the cycles makes changes in the systems responses in terms of mechanical and physical aspects. The responses of the building system to heat and thermal shock were analysed during the monitoring of the changes in temperature and deformation using sensors in a scalable prototype of a precast concrete wall system. In addition, a numerical simulation based on the finite element method (FEM) in commercial software was conducted to verify and analyse the variables in a digital model of the wall as a complementary study of the effects of heat and thermal shock. The results demonstrated the feasibility to use numerical simulation to analyses the phenomenal of heat and thermal shock on the behaviour of a precast concrete wall system.*

**Keywords:** *Thermal Shock, Durability, Numerical Simulation, Artificial Ageing, Building Systems.*

## 1. Introduction

The study of durability must consider the identification of agents that interact with buildings and their constructive systems and can affect their characteristics or properties over time, as addressed by ISO 19208:2016. In Brazil, a tropical climate country, some agents are more significant than in other countries such as the USA, Canada and countries in Northern Europe, particularly regard to high temperatures, humidity and ultraviolet radiation. The behaviour against these actions (e.g.: solar radiation and rain) is particularly significant in those systems located on the roofs and facades, as they are continuously exposed to solar radiation followed by a sudden cooling due to the occurrence of rain or of sudden environmental temperature changes, particularly in summer and winter, as discussed by BRIFFETT, (1991).

Therefore, one of the most important aspect for studying the durability of facades is their behaviour against cycles of high superficial temperatures and sudden cooling. If the temperature to which the facade is exposed varies rapidly, i.e., exposed to the “thermal shock” phenomenon, a temperature difference will be produced between the surface of the body and its interior in a short period of time can cause tensions of high magnitude. ASTM C1185-8 (2016), ETAG 004 (2013) and AS/NZS 2908-2 (2000) are foreign standards that assess the behaviour of walls in terms of heat and thermal shock. Such standards consider that the tests evaluation measure the “fatigue” of a specimen subjected to cycles of intense heat and thermal shock, being, therefore, considered an accelerated aging test.

In Brazil, the requirement of resistance to the action of heat and thermal shock is established for facade systems in ABNT NBR 15575-4 (2021). The evaluation criteria are the absence of cracks or failures, which could compromise the weathertightness performance system, during and after the test cycles, and the limitation of the specimen horizontal deflection. The test, according to ABNT NBR 15575-4 (2021), must be carried out on a specimen with dimensions equivalent to a representative facade wall section, considering all the constructive details of the wall, such as, the joints. Oliveira et al. (2014) analyses the methods of thermal shock tests in different standards and bibliographies and proposes modifications in the Brazilian method regarding to test specimen dimensions and connections. In some other national regulations, such as the SiNAT Guideline 003 (2016), the specimens must be at least 2.40 m width with borders restrictions. The test equipment consists of a vertical radiant source, a set of thermal sensors installed in the specimen and coupled to an automatic data acquisition equipment, and a water spray system for cooling the specimen. Despite all these studies, there are still lack of knowledge about methods using computer simulations to study the behaviour of facade systems subjected to thermal shock.

Thus, the objective of this article is to verify the feasibility of using a numerical model, using commercial software based on the finite element method (FEM), to study the behaviour of the facade subjected to the effect of thermal shock, by comparing the results obtained in the simulation to the values obtained from superficial temperature changes and horizontal deflections in a concrete wall instrumented and tested in the laboratory. The results show the importance of using computer simulation as an auxiliary tool for studying the durability of facade, mostly to new building systems, used in social housing (Martins, 2021; Ornellas, 2021).

## 2. Research Method

An experimental and numerical model was developed to analyse the responses of a concrete wall under the effect of heat and thermal shock. The wall performance was analysed by the monitoring of the superficial wall temperatures and the deflection variations (physical prototype built in the laboratory). In addition, a coupled transient numerical simulation was developed.

### 2.1. Experimental Program

The physical prototype consisted of a wall formed by two precast concrete panels, as normal for buildings, measuring 1.20 m (width) x 2.60 m (height) x 0.10 m (thickness) interconnected at two points by mechanical fastening. The vertical joint between the two panels has 0.02 m (width) x 2.60 m (height) x 0.10 m (thickness). The joint was filled with polyurethane-based sealant. The wall outer face was finished with white textured paint (Figure 1). The material properties are showed in Table 1. The prototype is fixed on its base and the horizontal displacement (deflection) are perpendicular to the constrained faces.

**Table 1** - Material properties of concrete wall containing a joint filled with polyurethane sealant.

| Properties \ Materials | Concrete | Polyurethane Sealant |
|---|---|---|
| Specific heat [J/(kg °C)] | 780 | 2 300 |

| | | |
|---|---|---|
| Density [kg/m³] | 2 300 | 950 |
| Thermal conductivity [W/(m °C)] | 0.72 | 0.28 |
| Thermal expansion coefficient [1/°C] | 1.4 x $10^{-5}$ | 2,3 x $10^{-4}$ |
| Young Module [GPa] | 30 | 1.1 |
| Poisson ratio | 0.18 | 0.42 |
| Strength Resistance (MPa) | 18.4 | - |
| Water absortion (%) | 9.9 | - |
| Void content (%) | 18.6 | - |

For the instrumentation of the concrete wall, ten thermocouples type T with PVC (polyvinyl chloride) insulation were used for temperatures and six PY-2-F-025-S01M deflectometers for horizontal and vertical deflections. Figure 1 shows the location of the sensors on the concrete wall. The thermocouples were installed on the external (TC1 to TC4) and internal (TC5 to TC9) facade faces, with the action of heat and thermal shock occurring directly on the external face. The TC10 monitored the temperature of the water used for the sudden cooling of the wall. Deflectometers DT1, DT2, DT4, DT5 and DT6 were positioned on the inner face and DT3 on the face above the wall near to the joint. Temperature and defection data were recorded through a data acquisition and recording platform. The heat action and thermal shock test considered the method proposed by ABNT NBR 15575-4 (2021) and SiNAT Guideline 003 (2016) with adaptations recommended by Oliveira et al. (2014) which consisted of exposing the wall outer surface to heating to a temperature of 80 ± 3 ºC, remaining constant for another hour. After this time, the same surface is cooled by a water sprinkler panel at a temperature of 20 ± 5 ºC until the wall outer surface reaches a temperature of 20ºC ± 5 ºC, generating a sudden variation in surface temperature, resulting in the effect of thermal shock. Two series of three test cycles were carried out to investigate the method. Heating was provided by a radiant panel containing seven sensors for monitoring the surface temperature. The heat action and the thermal shock were applied to the external face in the central region of the 1.20 m wide and 2.60 m high centralized wall.

## 2.1. Numerical Simulation

A three-dimensional numerical model was developed with characteristics and dimensions equivalent to the physical prototype (Figure 2). For simplifying, the two mechanical locking fasteners between the precast concrete elements and the white paint finish were not considered. The transfer of thermal energy (heat) occurred by conduction and convection, and the structural analysis was based on the linear elasticity theory. The base of the model was considered fixed (restricted) and the horizontal movements (perpendicular translation to the external and internal faces) were limited in the upper part.

The model consists of solid tetrahedral quadratic elements with one degree of freedom (temperature) for thermal analysis, and hexahedral quadratic elements with three degrees of freedom (displacements in the three directions x, y and z) for structural analysis. Contacts were considered perfectly adhered, that is, absence of adhesion failures. The finite elements of the mesh are approximately 50 mm size. The physical and mechanical properties of the numerical model were equivalent to the physical prototype.

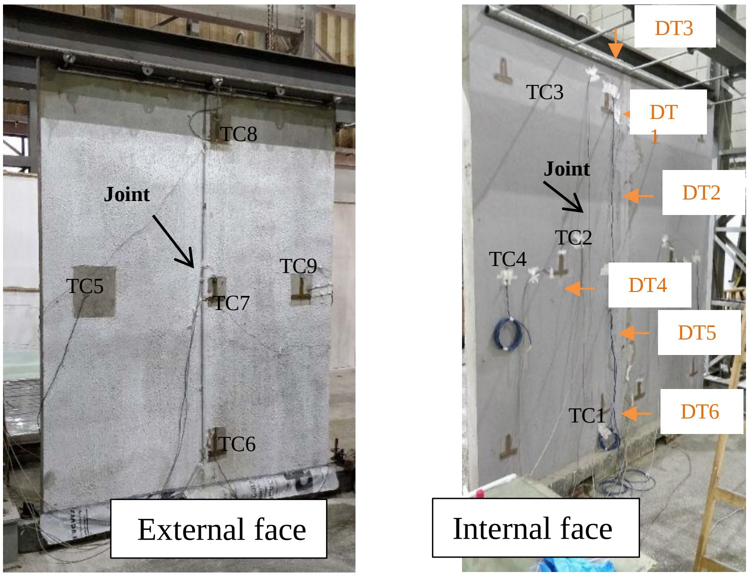


**Figure 1.** Physical prototype built with precast concrete wall containing a polyurethane joint, with the identification of the positioning of the monitoring sensors.

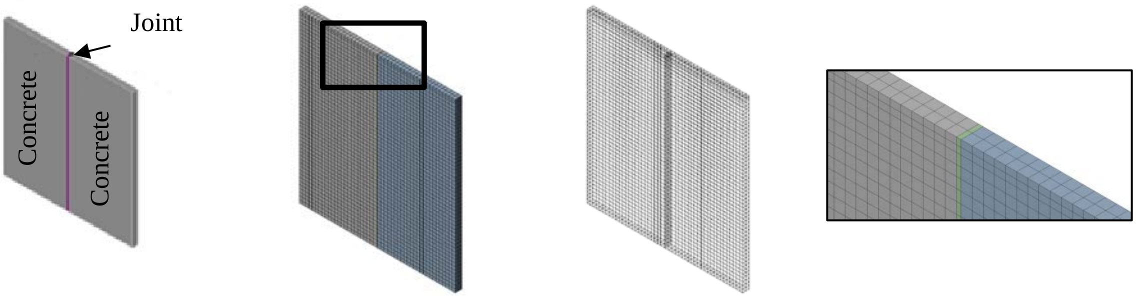


**Figure 2.** Numerical model and structure of the finite element mesh of the physical prototype containing a polyurethane joint.

A transient thermal simulation was carried out in order to reproduce the phenomenon of heat transfer, referring to a cycle of the sudden heating and cooling process, considering the effect of thermal shock, according to the method of ABNT NBR 15575-4. The simulation was divided into steps equivalent to the experimental program. Starting with (I) heating (2,100 W) of the external face of the wall until a temperature of 80 ± 3°C (ambient temperature equivalent to 23°C), keeping it constant for another hour. Then, (II) the sudden cooling was carried out through the suddenly reduction of the surface temperature on the same region provided by the negative heat (-600 w/m2) and, finally, (III) the removal of step II in order to establish equilibrium with the ambient temperature. The heat exchange by convection was considered as a function of temperature, being given by the equation: 3.784 W/(m^2 C) for 10°C, 6.71 W/(m^2 C) for 50°C, 7, 99 W/(m^2 C) for 100°C, according to theoretical values adopted by the software.

Finally, a transient structural simulation was carried out in order to reproduce the responses of the numerical model to the requests imposed by the thermal loads generated by the temperature variations obtained from the thermal simulation.

## 3. Results and Discuss

The Figure 3, Figure 4 and Figure 5 show the results of the temperature monitored on the surfaces of the inner and outer face of the wall during the thermal shock test cycles performed on the physical prototype in the laboratory and the numerical simulation. A more pronounced increase in surface temperature is noted at the beginning of the heating process, which gradually stabilizes as the temperature approaches 80ºC. Initial temperatures increase in a shorter period of time, that means, heat gain is faster at the beginning of heating where temperatures are closer to the ambient. The nomenclatures adopted for the sensors were continuous lines with the following legends: TCX for temperatures and DTX for deflections, with 'X' being the sensor number (1 to 9) related to the position; SY, sense 'Y' series 1 or 2; CZ, with 'Z' being cycle 1, 2 or 3. For the simulation, dashed lines with the legends TCX_S and DT0X_S for temperatures and deflection, were set. The red dashed line in Figure 3 represents the inner face, while the solid line represents the outer face.

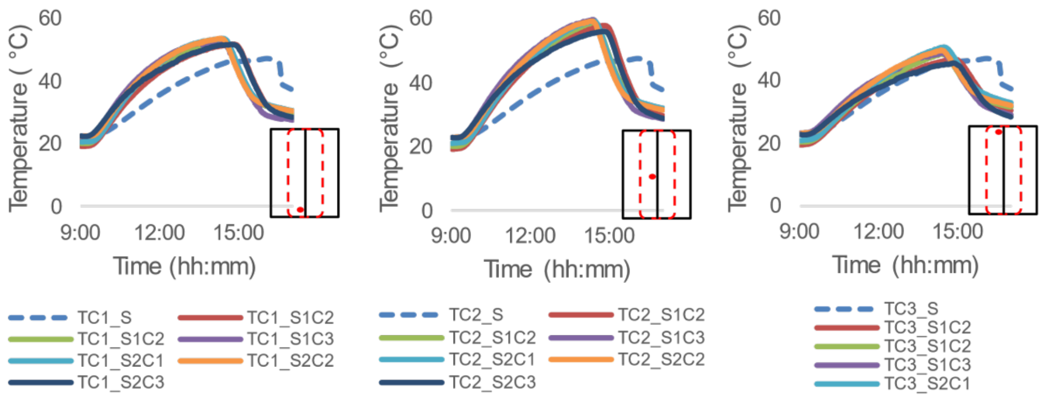


**Figure 3**. Distribution of experimental and numerical temperatures of the model for a test cycle at points TC1, TC2 and TC3.

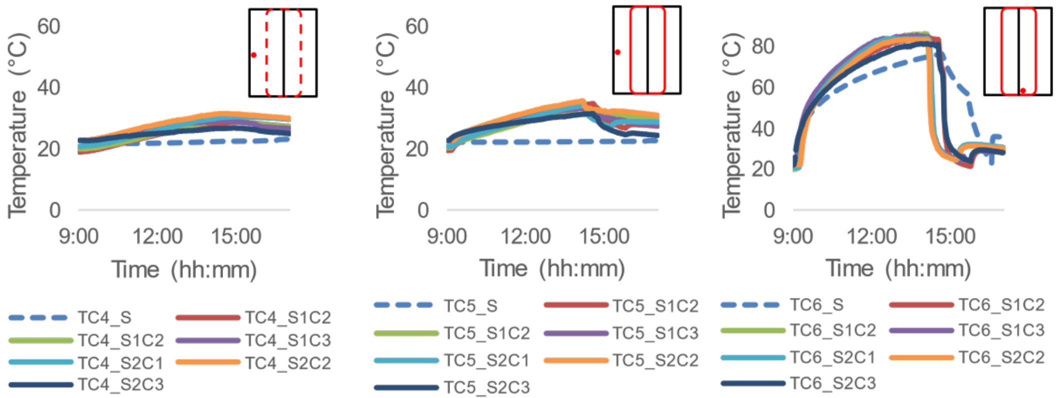


**Figure 4**. Distribution of experimental and numerical temperatures of the model for a test cycle at points TC4, TC5 and TC6.

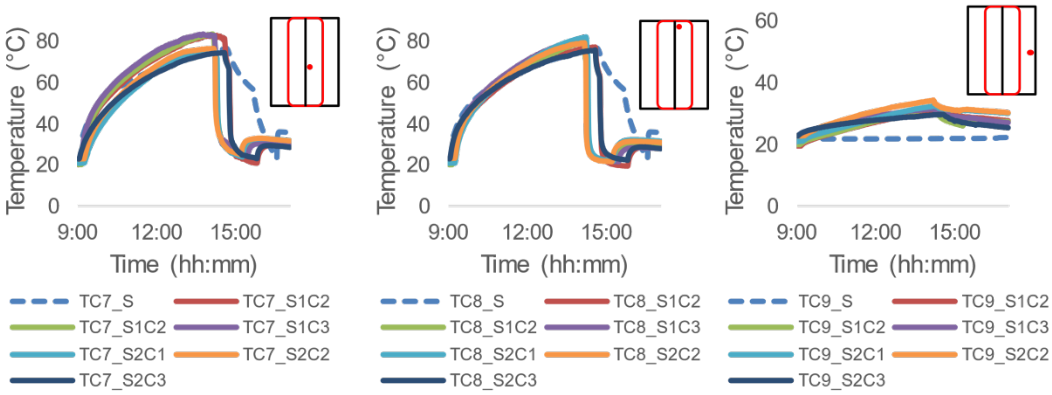


**Figure 5**. Distribution of experimental and numerical temperatures of the model for a test cycle at points TC7, TC8 e TC9.

A sudden temperature variation is observed in the external face region directly exposed to the effect of thermal shock (TC7, TC8 and TC9), different from the adjacent regions not directly heated (TC5 and TC9). Peaks of lower intensity values were identified on the inner face of the wall (TC1, TC2, TC3) in the region equivalent to the external face directly exposed to heat, except for the point located near the end of the model (TC4) which also showed little temperature variation. The monitored points outside the heating region of the internal and external faces (TC4, TC5 and TC9) were less influenced by the heat when compared to the other points. This may indicate that these regions are little influenced by thermal shock, even though they are located relatively close to the heating and cooling source. The computer simulation showed similarity to the experimental program relating to temperature distribution during the test cycle (TC1_S, TC2_S, TC3_S, TC4_S, TC5_S, TC6_S, TC7_S, TC8_S and TC9_S).

The Figure 6 and Figure 7 show the results of the linear deflections monitored on the inner face of the wall. The deflections showed a certain trend pattern of accentuated variation at the beginning of the heating process (DT01, DT02, DT4, DT5 and DT6). Unlike the temperature, they stabilized for a longer period, noted by the horizontal thresholds for points DT2, DT4, DT5 and DT6. This may indicate that the thermal inertia, given a certain value, does not cause significant variations in the horizontal deflections even the increase in temperature for the test conditions considered in this work. The deflections also followed a sudden variation caused by the thermal shock, observed by the peak values (close to 15h), as well as in the temperatures. This variation corresponded to the same instant of temperature drop, indicating that the system responds almost simultaneously to temperature changes. Vertical deflections (DT3) responded in the opposite way to the other monitored points, demonstrating that the wall was flexing (expanding) in the direction of heating and the upper region of the wall was moving vertically downwards. It was also noted that, just after the thermal shock, the horizontal deflections tended not to stabilize and become negative for a period equivalent to one hour of cooling, that is, they flexed to the opposite side before returning to what would be the its undisturbed state (period before the start of the first cycle).

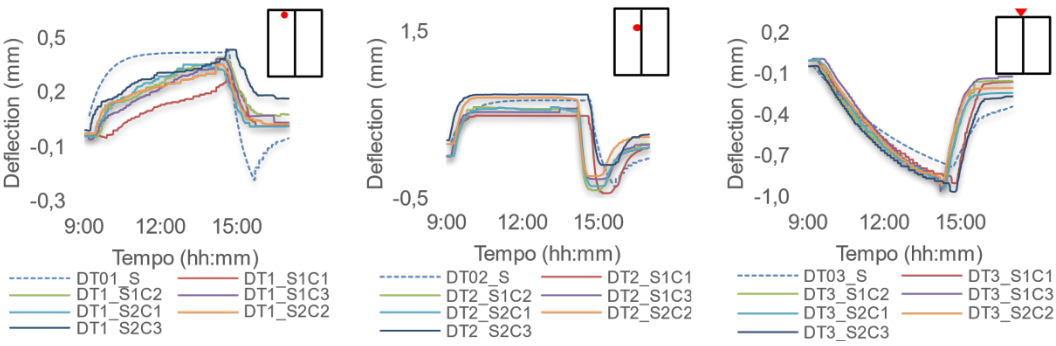


**Figure 6**. Distribution of deflections (mm) on the inner face of the wall during test cycles at points DT1, DT2 e DT3.

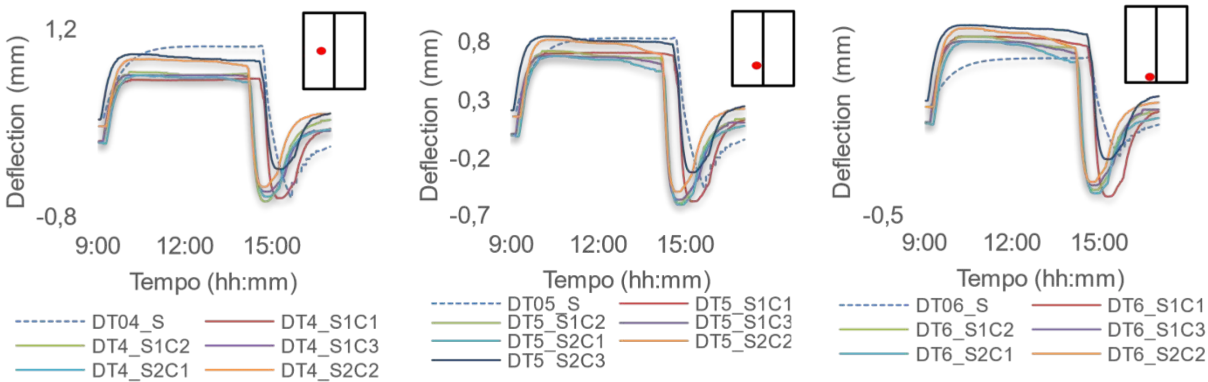


**Figure 7**. Distribution of deflections (mm) on the inner face of the wall during test cycles at points DT4, DT5 e DT6.

## 4. Conclusions

The numerical results demonstrated reasonableness regarding to the experimental results at the different monitored points in relation to the thermal shock cycles tested. It should be noted that the simplifications permit approximations to the numerical model, leaving the refinement of the boundary conditions to the experimental variables, such as the physical and mechanical properties of the physical prototype (coefficient of thermal expansion, modulus of elasticity, Poisson coefficient, thermal conductivity, heat specificity and density) and environmental conditions (heat exchange with the laboratory environment). The simulations can be used in the preliminary phases of the technical feasibility study, optimizing the time of the design and preliminary tests, helping adjustments and improvements less costly. Concluding, it is possible to adopt simplified numerical models for carrying out previous studies on the physical phenomenon of thermal shock in concrete walls, considering certain variables and restricted conditions. It is also necessary to evaluate the application of this model for the other vertical wall constructive systems.

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