CUSTOMIZING INSULATION MATERIAL PROPERTIES FOR BUILDING RETROFITTING: FROM INFRARED THERMOGRAPHY TO ADDITIVE MANUFACTURING

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ABSTRACT:

The European Commission proposed a recast to the Energy Efficiency Directive with a target of 30% energy efficiency for 2030. Buildings are the largest energy consumers sector in EU. To reduce the energy consumption of existing buildings and promote energy efficiency retrofit, it is important to improve the thermal performance of the building envelope, acting on thermal bridges to enhance the optimal thermal comfort for building occupants.

In this work, a customized solution is proposed combining IR thermography and a generative computer tool to design a functionally graded insulation layer tailored to specific conditions, resulting in a material efficient design reducing weight and material usage. AM technologies were then used to produce a scaled prototype.

KEYWORDS: (Additive Manufacturing, Building Retrofitting, Functionally Graded Materials, Infrared Thermography, Thermal Bridges)

INTRODUCTION

Climate change has already adversely impacted human health, natural ecosystems, and the economy (OECD, 2007). In 2011, a Flagship initiative called "Resource efficient Europe" (Copenhagen Resource Institute and ECORYS, 2014), was approved by European Commission, aiming at a greater resource efficiency and promoting economic growth and competitiveness. On the other hand, it is fundamental to actively seeking to reduce CO_2 emissions and encourage energy savings. On November 2016, the EU Commission proposed an update to the Energy Efficiency Directive with a new target of 30% energy efficiency for 2030 (European Commission, 2016).

In Europe, buildings account for 40% of total primary energy consumption and 36% of CO_2 emissions (The Economist Intelligence Unit, 2013) and new buildings represent only 1% in contrast with emerging economies such as China and India, where the demand for new buildings is

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huge. Stimulating building retrofitting can lead to clear energy saving and emission reduction targets for European cities (Lewis et al., 2013).

According to (OECD/IEA, 2013), space heating and cooling, combined with water heating, account for almost 60% of energy consumption in buildings. To reduce the energy consumption of existing buildings, it is fundamental to improve the thermal performance of the building envelope, enhancing this way the optimal thermal comfort for building occupants.

One of the primary solutions to limit the heat loss through the external envelope of the building is to correct areas with higher thermal conductivity than the surrounding materials, known as thermal bridges (Binggeli, 2016; Gorse et al., 2012). Traditionally, insulation solutions help to minimize energy loss. In building retrofitting, an additional layer of insulation material can improve the thermal capacity of an existing wall, correcting leaking areas. Available solutions in the market are typically composed by homogeneous materials with constant properties (Jelle, 2011). Additive Manufacturing (AM) technologies can be used to produce insulation solutions with specific properties (Craveiro et al., 2018). On the other hand, infrared (IR) thermography is a nondestructive tool that helps to diagnose building performance problems, including thermal bridges. In this work, an infrared camera was used to monitor the thermal properties of a house wall and detect potential localized thermal weaknesses. A computational tool was used to design a customized insulation layer to be applied onto the wall according to the specific thermal needs. The tool maps the thermographic image, obtained by a thermal camera during a cold winter night, generating an optimal material distribution corresponding to thermal bridges. It is most likely that a colder area needs more insulation than a warmer one, minimizing material usage and reduce energy consumption and CO_2 emissions. Figure 1 shows the proposed strategy.

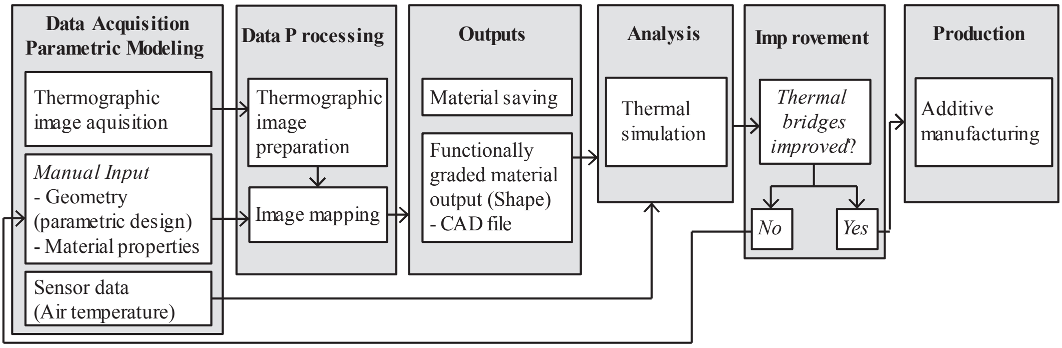

Figure 1. Overview of the proposed strategy.

Infrared thermography

The infrared thermography is commonly used to investigate the thermal conditions of building envelopes for retrofitting (FLIR, 2011; Khayatian et al., 2017). A thermographic camera can perceive the intensity of invisible radiation emitted by a surface, converting it into temperature and then display it as a thermal image (Eads et al., 2000). The infrared technique allows to qualitatively or quantitatively identify the distribution of radiant heat on a surface (Bisegna et al., 2014; Nardi et al., 2016), measuring the apparent temperature values. The surface temperature of an object is directly proportional to the amount of radiation emitted by the object (Baldinelli et al., 2018). A qualitative assessment involves the visual evaluation of the color pattern considering surface-heat variation for different surface areas, while the quantitative method entails quantifying temperature values to get a better understanding of the scale of the problem. A correct interpretation of thermal images is key to identify real defects (Lucchi, 2018).

Functionally Graded Additive Manufacturing

Additive Manufacturing (AM) technologies is a class of manufacturing processes, in which a part is built by adding layers of material upon one another (Ford, 2016; Rosen, 2016). There are different groups using AM technologies for the production of construction elements or retrofitting applications for both off-site and on-site applications (Craveiro et al., 2011; Dini, 2007; DUS Architects, 2014; Khoshnevis et al., 2006; S. Lim et al., 2009; Winsun, 2014). Current AM technologies are mostly used to fabricate physical elements with homogeneous material properties (Oxman, 2011; Sing et al., 2017), though the production of physical elements with spatially varying composition is being explored too (Craveiro et al., 2018, 2013; Mogas-Soldevila et al., 2014). These materials with a gradual spatial change in composition and microstructure, called Functionally Graded Materials (FGM) (Miyamoto et al. 1999), can be customized to specific thermo-mechanical loading conditions (Koizumi & Niino 1995), either through material varying composition (Craveiro et al., 2017b) or spatial porosity distribution (Craveiro et al., 2017a).

CASE STUDY

In this work, a north facing wall of a building room was investigated. The plan illustrated in Figure 2a shows that the wall under study is in contact with the exterior and other parts of the building. The indoor environment is naturally ventilated, and the electric heaters are 3m distant from the wall. This wall is composed by hollow clay bricks with plaster on both sides. The outside temperature was 3ºC (cold winter night), while the inside temperature was 20ºC. A thermal camera (FLIR) with an infrared sensor (320×240 pixels), represented in Figure 2a, was used to capture a 2D thermographic image that can be observed in Figure 2b. The temperature range of the camera is –20ºC to +1200ºC with a thermal sensitivity <0.045º at 30ºC and a field of view of 25º×19º (0.4m). Thermal bridges can be easily identified by the blue color, which represent cooler temperatures due to heat loss.

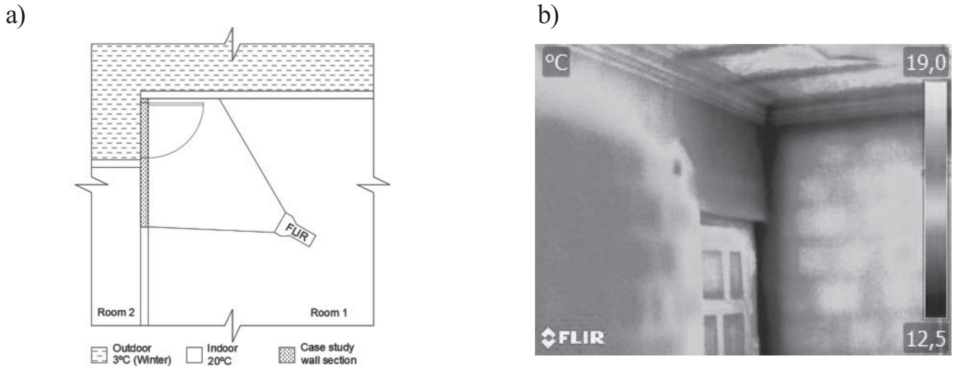

Figure 2. Thermal information measurement on a building room: a) FLIR camera position, b) Infrared image shows thermal patterns indicating areas of potential leakage.

Polyurethane (PU) foam is a good insulation material that can be used as boards (Jelle, 2011) and produced by AM technologies (Keating and Oxman, 2013). In this work, PU was selected as insulation material to correct thermal bridges The control of heat flow in buildings requires insulation layers and few thermal bridges. Considering thatcolder areas require more insulation material, so a design with perforated cylindrical holes (voids) only by one side (the inside one) can be a good solution to a more efficient material solution.

The insulation layer is intended to cover the entire wall, where the visible side is homogeneous and the internal one is composed by longer or shorter cylindrical voids, according to the thermal needs of the wall (Fig. 3a). The thermographic image (Fig. 3b) was adjusted and prepared to remove perspective distortions and unnecessary information using Adobe Photoshop CC2015.

A computational tool, developed by (Craveiro et al., 2017c) in Grasshopper (Rhinoceros plug-in) was adapted to be used in this case study (Fig. 3a). The insulation layer was parametrically designed and its maximum thickness (t) and cylinder radius (r) were kept constant. The layer thickness was settled to 60mm (t) to correct thermal bridging in colder areas, and it was considered 50mm for cylinder radius.

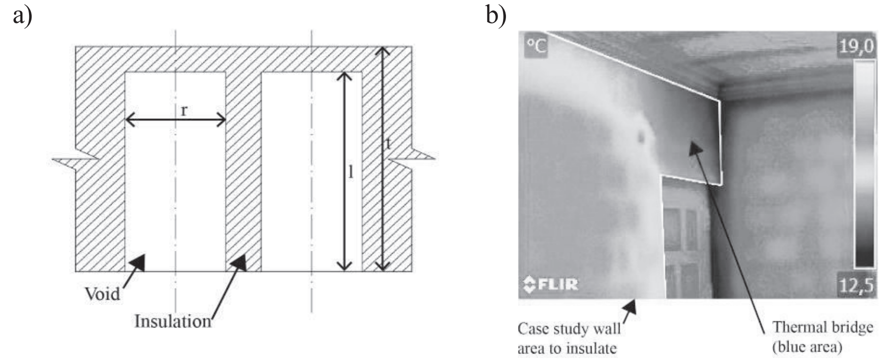

Figure 3. Case study: a) parametric insulation layer, b) area to be insulated.

The image was mapped using an image sampler script, which converts visual information into a series of numerical outputs. The data was analyzed through an algorithm, attributing a distinct cylinder void length (l) according to the thermal needs of each location. Colder areas require shorter cylinder void lengths and warmer areas longer ones.

The generative code developed in visual programming language (VPL) and interface can be observed in Figure 4a, while Figure 4b shows the output solution for the insulation layer obtained from Rhinoceros.

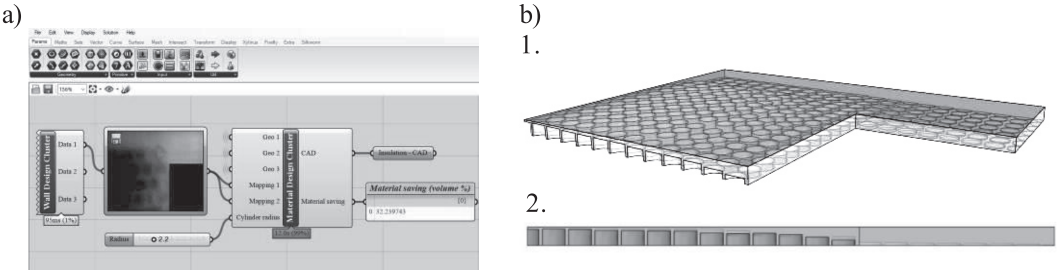

Figure 4. Algorithmic code using VPL language: a) Grasshopper code, b) Insulation layer Rhinoceros 3D Output: 1. View in perspective, 2. bottom view.

Thermal Simulation

A simulation was performed using a Finite Element Analysis (FEA) software, called Solidworks Simulation (2016), to get the thermal performance of the generated insulation layer. The generated CAD model was then imported and a FEA mesh of tetrahedral elements was created, PU properties [thermal conductivity: 0.023 W/(m^2×K); mass density: 30 kg/m^3] and boundary conditions were applied. On the interior side of the insulation layer, in contact with the wall, the temperature loads were applied at the base of the cylinder voids according to the thermographic image. The temperature value distribution was converted in 3 main areas, corresponding to 13ºC, 15ºC and 17ºC respectively. On the visible side, a convection load of 20ºC with convection coefficient of 10 W/(m^2×K) was applied, corresponding to the indoor measured temperature. Figure 5 shows applied loads.

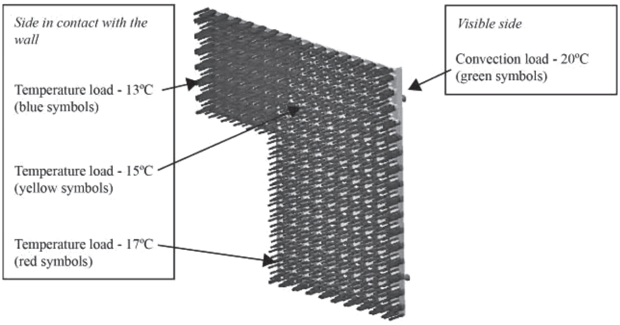

Figure 5. Thermal loads applied to the generated insulation layer.

The thermal simulation result is illustrated in Figure 6, where a) represents the interior side, and the temperature distribution naturally represents the 3 abovementioned areas with different temperatures, b) displays the visible side, indicating a homogeneous distribution between the thermal bridge and the remaining zone. Cross sections of the insulation panel are presented in c) and d).

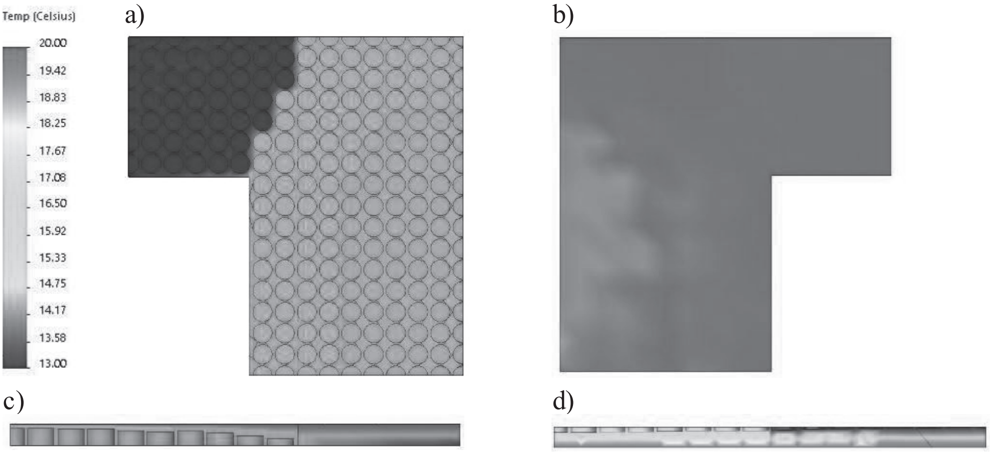

Figure 6. Solidworks thermal simulation results of the insulation generated layer: a) interior side, b) visible side, c) and d) cross-cut sides.

The customized functionally graded perforated layer reduced in 32% the volume of material usage, compared to a traditional compact insulation layer. According to simulation, the performance of the remaining insulation material is sufficient to correct the thermal bridge, as can be observed in Figure 6b.

Prototype production

To assess the pilot design, a scale model of the generated insulation layer was then produced by AM technologies through a FDM 3D printer, adding successive layers of a black polymer. A .STL file was exported from Rhinoceros and CURA software was used to create the printing path (Fig. 7a). The prototype can be observed in Figure 7b, where each cylindrical hole has a specific depth to minimize material usage. The customized layer keeps a constant thickness between holes to ensure a correct adjustment to the wall.

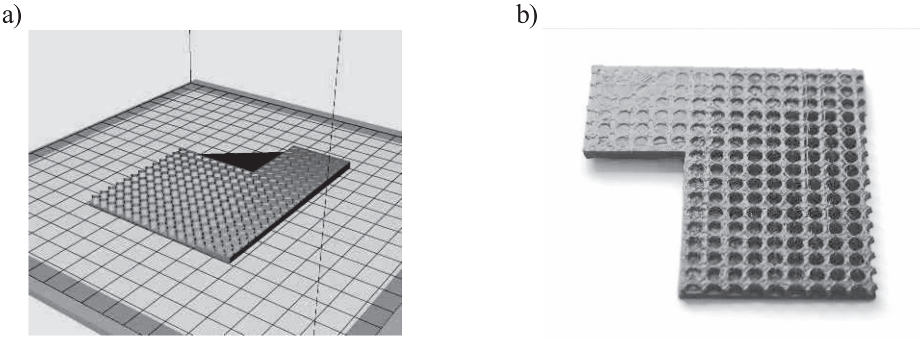

Figure 7. Prototype production: a) 3D printer interface (CURA), b) produced part.

CONCLUSIONS AND FUTURE WORK

One of the priorities of the European Commission is to enhance resource and energy efficiency. Retrofitting existing buildings with better energy efficient solutions can reduce costs and promote thermal comfort for building occupants.

In this work, a solution is proposed to assist in the correction of thermal bridges, limiting the heat loss through the external building envelope. The application of the FGM concept to customized building insulation tailored to specific conditions, minimizes resource usage. This new strategy combines IR thermography, a generative tool and AM technologies to create a customized functionally graded insulation layer. The next step will be to build a full-scale prototype using a robotic arm with a PU foam extruder.

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