Analyses of resistance of openings to Pyroclastic Flows

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Abstract: During an explosive volcanic eruption, constructions are hit by various inertial or surface actions often associated with high temperatures, that can cause fires and/or explosions that can affect the mechanical properties of structural and non-structural elements. Among the volcanic phenomena the pyroclastic flows have a devastating effect. They are a gas-solid mixture, which can flow slope down up to reach considerable distances from the point of emission, a speed that can easily exceed 100km/h (~ 30m/s). Their temperatures may be higher than 400°C and they cause casualties and problems to the structures. The action exerted by pyroclastic flows on buildings is a dynamic pressure accompanied by high temperatures. The experience of the eruption in Montserrat (British overseas territory in the Caribbean) in 1995 has shown that the openings of buildings are particularly vulnerable to the stresses caused by pyroclastic flows, even when the static nature of the building itself is not compromised, the risk associated with the passage of the flow in the internal environments following the breakthrough of the openings is therefore significant, increasing the risk of fire inside the building. In this work, the objective is to contribute to the understanding of resistance of the characteristic openings of buildings potentially at risk along the flow path, considering the dynamic pressures and temperature ranges associated with a specific scenario at Vesuvius and the Campi Flegrei, volcanoes (Campania Region, Italy) defined in the National Emergency Plans.

Keywords: Mitigation strategies; Volcanic risk; Pyroclastic flows.

1. Introduction

Explosive volcanic eruptions can cause casualties and economic losses unless appropriate mitigation measures can be taken. Inside the metropolitan area surrounding the city of Naples (Campania Region, Italy) there are two active volcanic systems, the Somma-Vesuvius and the Campi Flegrei, whose geological history allows to believe that they will be able to produce, in the future, some explosive eruptions. The hazard of both volcanoes, the high exposed value of the urban area, which counts about three thousand people, and the high vulnerability of the urban settlements make the Neapolitan territory one of the riskiest volcanic areas (Zuccaro and De Gregorio, 2011). Volcanic eruptions encompass different hazards as volcanic earthquake, ashfall, pyroclastic flows and subsequent floods and mudflows. The most dangerous phenomenon is the pyroclastic flows, which can occur with little warning, move at high speeds, and have enormous destructive power (Spence et al., 2010). Although the Emergency Plans provide for the preventive evacuation of the areas affected by the phenomenon, the protection of the openings represents the main objective as it happened during the volcanic eruption on the Caribbean island of Montserrat

(British Overseas Territory), the openings and especially the unprotected ones were the first elements of the building envelope to be compromised and causing considerable damage to the structure itself. Therefore, such a strategy would allow for faster and cheaper recovery action.

Glass breakage, in the presence of pyroclastic flows, can occur both because of the acting pressures (3 - 7 kPa) and because of the high temperature that can occur by conductive and radiative exchange from the hot materials of the flows themselves. The temperature increase of the transparent surface will cause local expansion and breakage. The forecast temperature represents an important issue to be tackled since some of the windows' components are thermoplastic. Indeed if they reach their temperature of glass transition (Tg), they soften, and it is possible to hypothesize in the case of gaskets the leakage of the seal between the glass pane and the frame, whilst in the case of polyamide the loss of continuity between aluminium sections; so the probability of the failure of the window can be considered very high. To deal with these issues and consequently define the appropriate mitigation strategies, this study shows a different method to assess the vulnerability both for the pressure and for the temperature. Finally, the research includes developing methodologies for the modelling and evaluation of technical solutions, design guidelines, demonstration projects and prototype components for the realization of new industrial products for the building envelope aimed at volcanic risk mitigation and energy saving.

2. Volcanic Phenomena

The Emergency Plans, developed by the Italian Civil Protection Department, are a useful tool for mitigation of volcanic risk, which starts from the examination of the hazard of the volcano (through the choice of the reference event), the exposure of the elements affected by the eruption (people, buildings and infrastructure) and their vulnerability to the eruptive phenomena. Explosive eruptions are expected for Vesuvius, and the Campi Flegrei, characterized by the formation of a sustained eruptive column several kilometres high, the fallout of volcanic bombs and stone blocks near the crater and smaller particles (ash and lapilli) even several tens of kilometres downwind, as well as the formation of pyroclastic flows that would flow along the slopes of the volcano for several kilometres. For the Campi Flegrei, unlike what happens in volcanoes with central apparatus, such as Vesuvius, the area of the possible opening of the eruptive vent is huge; moreover, regarding fallout, it should be considered that, unlike Vesuvius, the city of Naples is downwind of the dominant winds and would therefore be involved. For Vesuvius, as scenario, it has hypothesized a Sub-Plinian event, corresponding to a volcanic explosivity index VEI =4), with a conditioned probability of occurrence preferably less than 30% (Marzocchi et al., 2004). On the other hand, for Campi Flegrei, as eruption scenario, a medium-size event was assumed to occur with a conditioned probability of occurrence rather than about 24% (Costa et al., 2009). The seismic events that characterize an eruptive phenomenon can be generally considered of low-medium intensity. Considering a sub-Plinian I eruption scenario, there would be a marked increase of low magnitude in the pre-eruptive phase and the occurrence of a low to medium magnitude. Some of these precursor events may exceed the size threshold that can cause damage, including severe, to buildings and infrastructure in the areas surrounding the volcano. The initial phase of a sub-Plinian eruption is characterized by the formation of a sustained eruptive column of gas-solid pyroclastic dispersal. It represents an excellent risk for existing buildings because pyroclastic solid material of various size falls to ground from the eruptive column dispersed by wind and the affected area has frequently an elliptical shape elongated in the direction of the wind. Grain size and thickness of ash fall deposits decrease with the eruptive vent's distance and is generally uniform over small areas.

The pyroclastic flows are the most dangerous volcanic phenomenon produced by a sub-Plinian eruption. They are generated by the gravitational collapse of the eruptive column at the end of the ash fall phase. The pyroclastic flows are a suspension of gas and solid particles of various sizes. Their hazard at Vesuvius had been studied by numerical modelling by Todesco et al. (2002) and Esposti Ongaro et al. (2002). In structural assesses to evaluate the vulnerability, the action due to pyroclastic flows could be considered a uniformly distributed static pressure (Petrazzuoli and Zuccaro, 2004), within a temperature range between 200 and 350 °C (Gurioli et al. 2008). In previous studies, (Esposti Ongaro et al. 2008; Neri et al. 2007), through a 4D model, the Vesuvius was schematized with its real geometric dimension, and the variable time is included. After 900 s since the pyroclastic flow's origin, a pressure of 1-3 kPa at 7.5 km from the vent, with a temperature of 250 °C was assessed.

The experience from the 1997 Montserrat eruption (UK Caribbean Islands) had shown that a building could withstand moderate pyroclastic flows pressure (1–5 kPa), whereas if one or more openings (windows and doors) fail, allowing hot gas and ash to pass in, the entire building is likely to be destroyed (Baxter et al. 2005). In this case, the contents of the construction and any timber structure are likely to catch fire; simultaneously, the principal structural walls and roofing will suffer a combination of internal and external pressures, which will cause partial or total failure (Spence et al. 2004a). In general, the first elements to collapse are the glass windows and the shutters. Nevertheless, a building's lateral resistance to pyroclastic flow strongly depends on the design criteria applied to resist ordinary load conditions: of course, an earthquake-resistant building has more considerable strength and stiffness capabilities than a non-seismic building. The structural behaviour of buildings under pyroclastic flows is not comparable to that induced by earthquakes, since the horizontal pressure is not a cyclic action. So, the structural response is less influenced by the ductility, like the capability to dissipate energy.

3. Exposure

3.1. Description of building data of Vesuvius and Campi Flegrei areas

In order to define the best mitigation strategies, it has been necessary to arrange some available data about the buildings in the areas that will be evacuated before the eruption (called 'red zones'), gathered up by the P.LIN.V.S. Among these data, the useful ones for the purpose are the vertical structure, material of frame and shutters. Indeed, different openings are used in the different structures both in the Vesuvian and Phlegrean areas; there is a wide diffusion of buildings framed in reinforced concrete with thick infills panels and masonry structures with square blocks in brick or tuff. Besides, there is a widespread diffusion of aluminium and wood windows with UPVC shutters for both the areas (Fig.1, Fig.2). In this study, the most studied openings are the windows, which, together with the doors, represent a weak point of the building envelope during a pyroclastic flow event (Spence et al. 2004). since the dynamic pressure exceeds the characteristic resistance of them, increasing the vulnerability. So, the data about openings have been divided into three groups:Size of openings;

- Frame types;
- Shutters types.

Each of these characteristics is important in assessing the vulnerability and so in defining the adequate mitigation measures. Besides, the sizes of openings were recorded in three classes:

- Large windows, whose area is greater than 1,5 m^2;

- Typical windows, whose area range from 0.5 to 1.5 m^2;
- Small windows, whose area is less than 0.5 m^2.

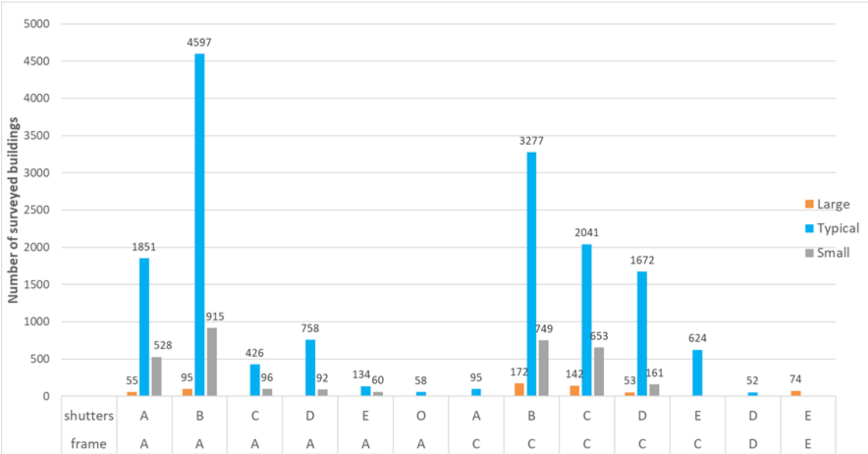

Figure 1. Number of windows in Vesuvius area divided by size and material

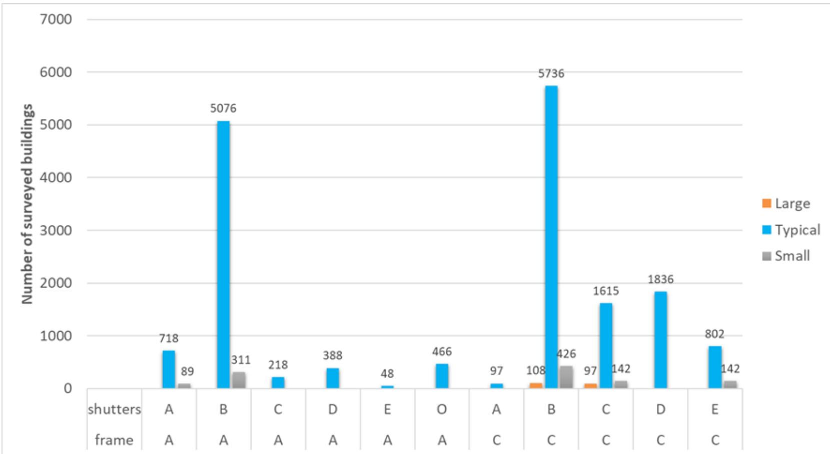

Figure 2. Number of windows in Phlegrean area divided by size and material.

3.2. ALUMINIUM WINDOWS

The EN AW-6060 alloy is the most widespread extrusion alloy on the European market, thanks to its high hot forming speed. The alloy allows the production of profiles with even complex sections, including cavities and multiple grooves, to bring the design of the extruded part as close as possible to that of the finished product and to minimize intermediate machining. The mechanical model used is Ramberg-Osgood (1) and the characteristics of the alloy are (Table 1):

Table 1 Physical and mechanical properties of aluminium EN-AW 6060	
Density	2700 [kg/m^3]
Elastic modulus	70000 [MPa]
Breaking voltage	160 [MPa]
Poisson’s ratio	0.33
Specific heat capacity	900 [J/kgK]
Thermal conductivity	238 [W/mK]
Thermal expansion	3,7 e^{-7} [1/K]

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{\sigma_y}\right)^{\frac{1}{n}} \quad (1)$$

- σy is the yield strength of the material,
- σ is the value of the stress considered,
- E Young's modulus,
- n exponent of the hardening of the material.

The type of glass commonly used is composed of silica oxide and lime. As defined in the Instructions for the design, execution and control of constructions with structural glass elements, the latter can be considered a homogeneous, isotropic material with linear elastic behaviour at breakage, both tensile and compressive. The characteristics of this type of glass (Table 2) are:

Table 2 Physical and mechanical properties of soda lime glass	
Density	2400 [kg/m^3]
Elastic Modulus	71000 [MPa]
Ultimate Tensile Strength	41 [MPa]
Compressive strength	300 [MPa]
Poisson’s ratio	0.33
Specific Heat Capacity	800 [J/kgK]
Thermal Conductivity	1 [W/mK]

The technology hypothesized, as the most common, is that of insulating glass, which indicates the set of two or more sheets of equal or variable thickness, separated by a cavity, usually of air. For the analyses, two panes of the same thickness, i.e. (4/5/6) mm. The geometric model used is thermal break window and door frame (Fig. 3).

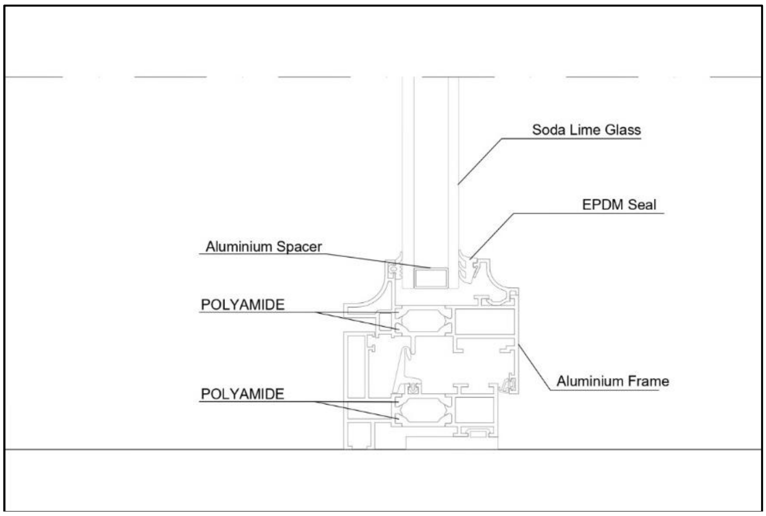

Figure 3. Thermal break aluminum window section.

3.3. Timber windows

The wood is the other material widespread in the Campi Flegrei and Vesuvian area for the construction of windows and doors. The choice of this material depends mainly on the good thermal insulation characteristics compared to UPVC and aluminium windows and doors. In fact, this choice is economically disadvantageous because wood is certainly a more delicate material compared to UPVC and aluminium, as it requires regular maintenance, and because the price of wooden windows and doors is still higher than that of aluminium and PVC.

There are several species of wood, belonging to the broadleaf and conifer families, used for the construction of windows and doors:

- chestnut,
- fir,
- pine.

Besides a first hypothesis was to consider the material as a homogeneous and isotropic, whose behaviour has been hypothesized linear elastic until breakage. Therefore, the characteristics of the two wood species (Tab. 4, Tab. 5).

Table 4 Physical and mechanical properties of Pine	
Density	532 [kg/m^3]
Elastic Modulus	13700 [MPa]
Tensile Strength	85 [MPa]
Compressive Strength	45 [MPa]
Poisson’s ratio	0.33

Table 5 Physical and mechanical properties of Chesnut	
Density	630[kg/m^3]
Elastic Modulus	114000 [MPa]
Tensile Strength	95 [MPa]
Compressive Strength	51 [MPa]
Poisson’s ratio	0.30

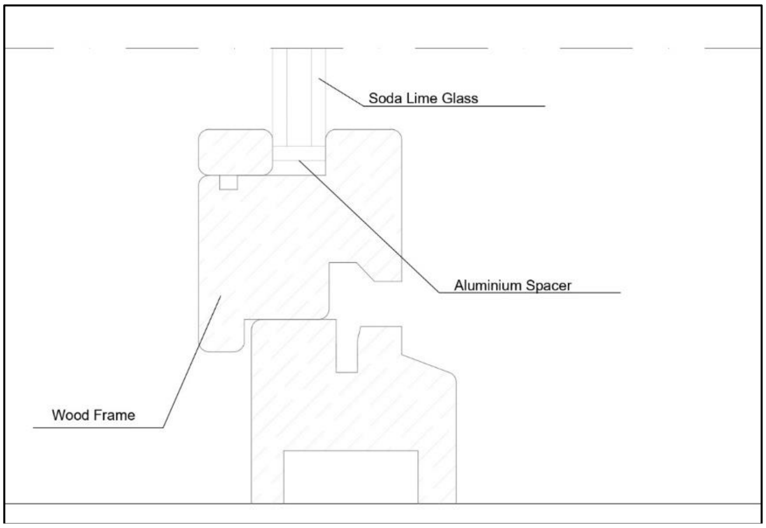

Figure 4 Wood Windows.

3.4. UPVC WINDOWS

Another common material to produce windows and doors is UPVC. UPVC is a material composed of macromolecules which are in turn formed by hydrogen, carbon and chlorine atoms. A UPVC window and door frame has very similar characteristics to those of wood. UPVC has a low mechanical resistance; to overcome this, multi-chamber profiles are extruded and reinforced with the help of metal elements (Fig.5). These windows and doors have the main characteristic of resisting very well to the aggressions of atmospheric agents, are very light and offer good thermal insulation (Mottura and Pennisi, 2014). UPVC is a thermoplastic so its mechanical characteristics (Tab.6) are highly dependent on the glass transition temperature (T_G); that is the temperature, below which the physical properties of plastics change to those of a glassy or crystalline state. Above T_g they behave like rubbery materials. Below the T_g a plastic’s molecules have relatively little mobility (Ebnesajjad, 2016) so the material behaves as a fragile and rigid material. UPVC has a glass transition temperature of 80°C. Thus, considering the temperatures expected in the red areas, UPVC windows and doors are not suitable to withstand the pressures applied by the pyroclastic flows.

Table 6 Physical and mechanical properties of UPVC

Density	1400 [kg/m^3]
Elastic Modulus	3700 [MPa]
Tensile Strength	47 [MPa]
Coefficient of thermal expansion	0,8e^{-4} [1/K]
Poisson's ratio	0.40

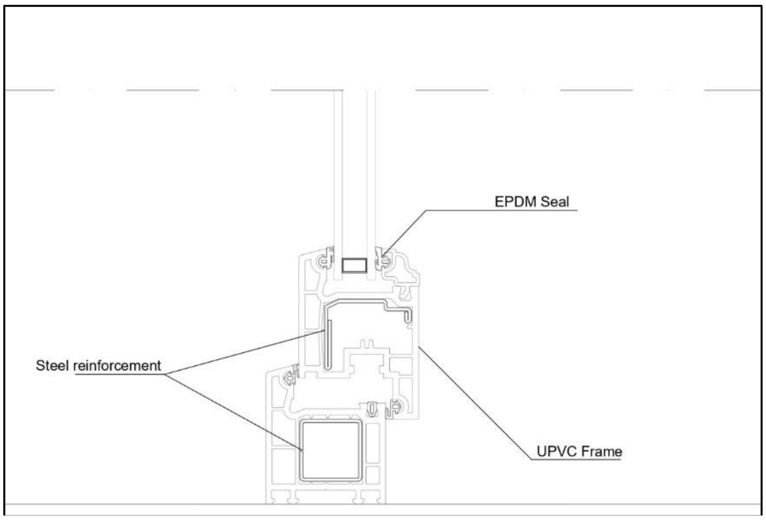

Figure 5. UPVC windows.

4. Vulnerability Assessment

To assess the vulnerability of the frames to the pressures expected in both areas, a two-dimensional stationary linear static model (2) has been set up for both aluminium and wooden frames.

$$0 = \nabla \cdot S + F_V \quad (2)$$

where:

- $\nabla \cdot S$ is stress tensor (Pa),
- F is the applied force (N/mm)

Since the resistance of openings to dynamic pressure depends on several factors of which the most important are the size; therefore, three different heights have been considered for each group of windows, i.e. for the large openings a height of 2.4 m had been considered, for the Typical a height of 1.2 m and for the small a height of 0.8 m has been considered; and for each window size the different thicknesses of the glass have been considered. Furthermore, it has been considered a fixed constraint at the base of the wall on which the window is placed (Fig.3). Additionally, it has been considered half section in order to reduce the computational time, assuming a condition of symmetry in the upper part of the window.

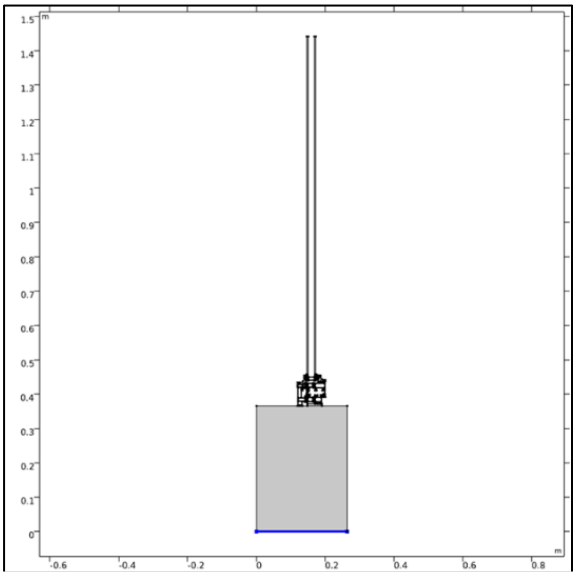

Figure 6. Fixed constraint condition-

Finally, a uniformly distributed load applied (3) on the external front has been assumed, in favor of opening, which is linearly variable according to a parameter that has been imposed through a range function.

$$\boldsymbol{S} \cdot \mathbf{n} = F_A \tag{3}$$

$$\boldsymbol{F_A} = \frac{F_L}{d} \tag{4}$$

From these first mechanical analyses, the glass is the first element of the fixed system to fail (Tab.7). In particular, the glass of 4 mm of large dimensions, therefore with dimensions equal to 2.4 m of height and 0.6 of width, is the most vulnerable because the calculated breaking pressure is equal to 0.6 kPa. This situation is not entirely similar for wooden frames, as the glass of this type is placed inside the frame without the aid of gaskets, so the glass is perfectly embedded in the frame itself. Although the glass in the case of wooden frames may be suitable to withstand the expected pressures, the problem lies in the resistance of the glass to temperature variation.

Table 7 Glass breakage load aluminium windows

Frame	**Glass**								
Aluminium	SODA LIME GLASS								
	Large			Typical			Small		
	4mm	5mm	6mm	4mm	5mm	6mm	4mm	5mm	6mm
	0,6 kPa	1 kPa	1,3 kPa	2 kPa	3 kPa	4,3 kPa	5,3 kPa	8 kPa	10 kPa

Table 8 Glass breakage load timber windows

Frame	Glass								
Wood	SODA LIME GLASS								
	Large			Typical			Small		
	4mm	5mm	6mm	4mm	5mm	6mm	4mm	5mm	6mm
	2 kPa	2.3 kPa	3.3 kPa	4.6 kPa	6.6 kPa	9.6 kPa	8.6 kPa	14.6 kPa	22.6 kPa

4.1. Mitigation Strategy

An initial mitigation strategy, suitable for making glass capable of withstanding high pressures, could be the use of laminated glass technology.

Laminated glass for architectural glazing applications consists of two layers of glass bonded to a thin thermoplastic interlayer. The interlayer is responsible for keeping the glass fragments together after breaking, while increasing the residual strength of the material. There are different types of interlayer depending on the material used, the most used is Polyvinyl butyral (PVB) even though it has low mechanical qualities. Currently a new type of interlayer produced by Dupont® is also used, the

Sentry Glass Plus (SGP) which, unlike the previous one, presents a resistance relatively high. This hypothesis of mitigation is not suitable for the pyroclastic flow, since these interlayers are thermoplastic, and their behavior depends on the temperature of exposure. Indeed, above the 80°C the PVB film starts to separate from the glass (delamination); besides, the SGP structural interlayer is also characterized by a melting temperature of 94°C.

5. Thermal Analysis

5.1. Thermal Shock

Once the mechanical vulnerability had been defined, a first thermal analysis of the transparent elements was carried out, in particular the exposure time at three different temperatures (100/200/300) °C was calculated, until the critical temperature that causes the glass to break due to the thermal shock, considering both the three different thicknesses and the three different dimensions previously defined. Thermal shock occurs when a thermal gradient causes different parts of an object to expand in different quantities. This differential expansion can also be understood in terms of stress or deformation (5) At some point, this stress may exceed the strength of the material, causing a crack to form. If nothing prevents this crack from propagating through the material, the glazing will lose its structural integrity. Glass objects are particularly vulnerable to failure due to thermal shock, due to their low strength and low thermal conductivity. If the glass is then suddenly exposed to extreme heat, the shock will cause the glass to break.

$$\Delta T = \frac{(\sigma_{TS} * (1 - \upsilon))}{E * \alpha} \tag{5}$$

where:

- σ_{TS} is the yield strength of the material,
- ν Poisson’s ratio,
- E Elastic modulus,

- α coefficient of thermal expansions.

In the case of soda lime glass, the critical temperature is 52 °C.
Once the critical temperature is defined, it has been necessary to assess the time to reach it through the heat transfer equation (6)

$$d_z \rho C_p \frac{\delta T}{\delta t} + d_z \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot q = d_z Q \quad (6)$$

where:

- ρ is the density (kg/m^3),
- Cp is the specific heat (J/(kg*K)),
- T is the temperature (K),
- u is the speed vector of motion (m/s),
- Q is the heat source (W/m^3),
- dz is thickness of domain in the out-of-plane direction (m),
- q is the conduction heat flow (W/m^2).

To model this problem properly, a time-dependent study was used in the 60 second interval using the range function (0.1.60) s. Moreover, to model the sudden temperature rise, a ramp function (Fig.7) was applied in the Temperature node, using the following expression:

$$20 + x * ramp(t) \quad (7)$$

where variable x is equal respectively to 80, 180, 280 and 380°C so that the glass is subject to three different maximum temperatures: 100°C, 200°C and 300°C.

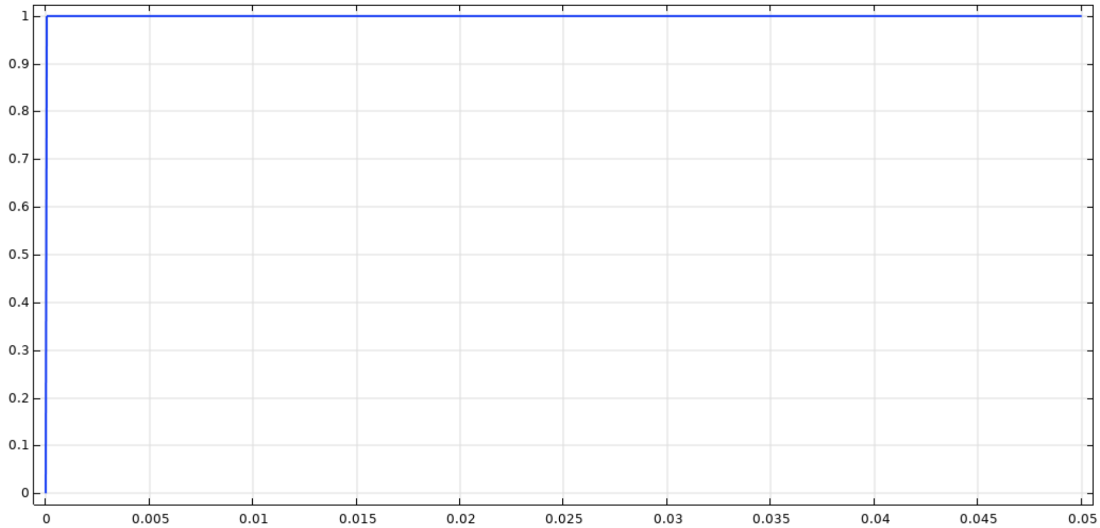

Figure 7. Ramp Function.

From this kind of analysis considering an applied temperature of 100 °C, soda-lime glass reaches the critical temperature in the 5-second time interval. (Fig 8). Therefore, soda-lime glass is totally vulnerable to the temperatures expected in the red areas.

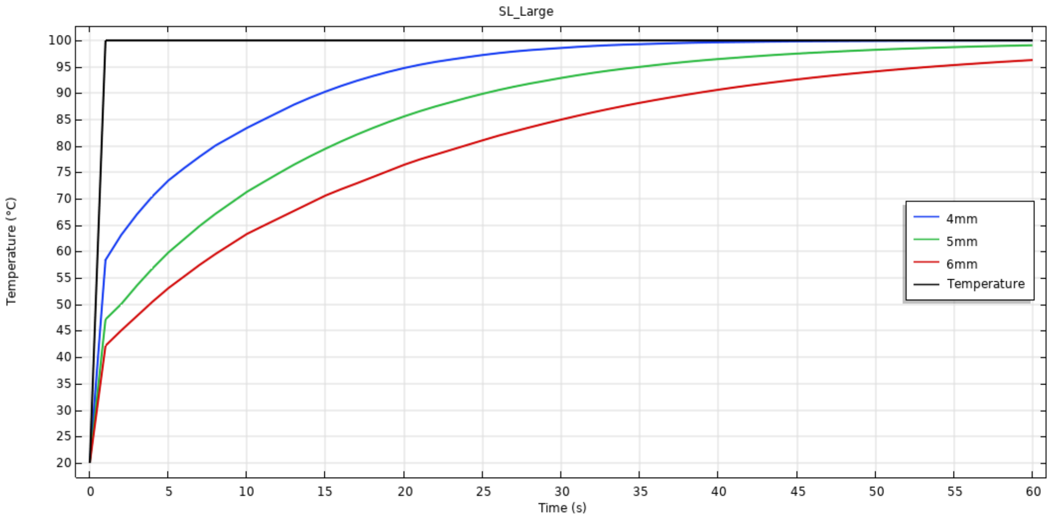

Figure 8. Heat Transfer for large glass pane.

5.2. Aluminium Resistance

In order to analyse the resistance of the aluminium frame, the stress due to the agent temperature (8) was calculated, which was applied, for a time interval of 1200 s, through the ramp function (6). The first results show that the aluminium can withstand, as there is no breaking-strength of 160 MPa, for the expected temperatures. On the other hand, the time of reaching the glass transition temperature of the polyamide that constitutes the thermal break of the frame was also evaluated, since once this temperature of 50°C has been reached, the material softens and therefore the solution of continuity between the two aluminium sections constituting the frame and counter frame is lost and therefore the breakage of the frame. In the case of the aluminium frame with thermal break, the polyamide reaches this temperature in a range of 490s in the case of 100°C, while in the case of 200°C and 300°C the time is reduced to 50s and 20s respectively (Fig.10).

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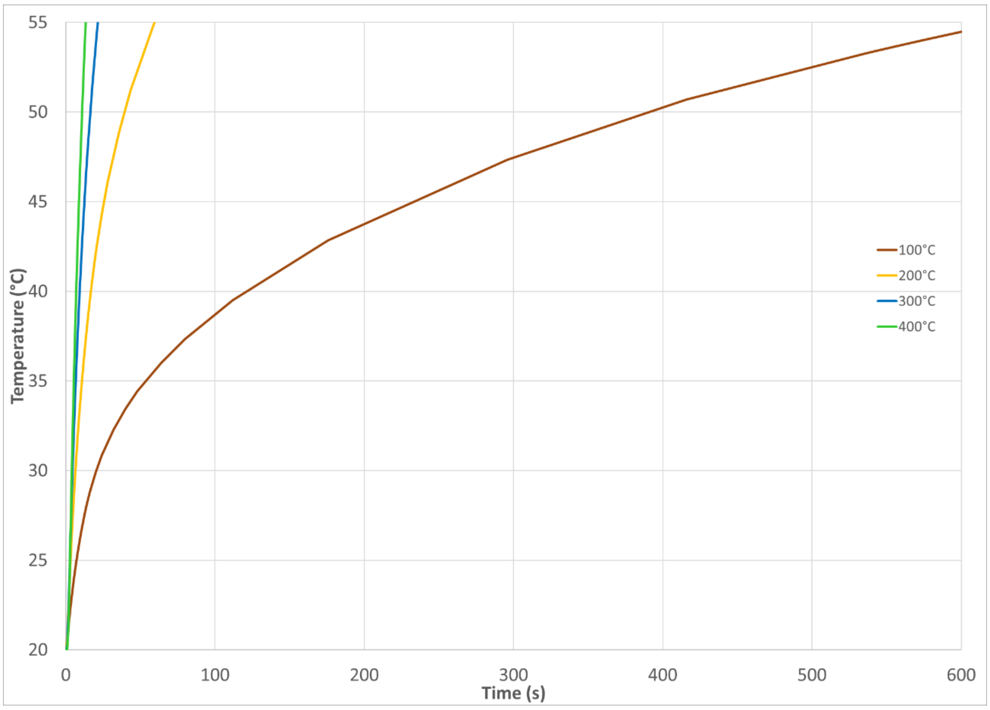

Figure 9. Temperature of Polyamide of Unprotected Section.

$$\varepsilon_{th} = \alpha(T)(T - T_{ref}) \quad (8)$$

5.3. Mitigation Strategy

A mitigation strategy for this problem is to replace glass with one that has good thermal shock resistance, i.e. tempered glass. This is a type of safety glass treated with controlled thermal or chemical processes to increase its resistance compared to normal glass. When (5) is applied, the critical temperature calculated, considering the characteristics of such glass (Table 9), is 355 °C. Therefore, this option could be suitable for urban settlements present at distances very far from the vent, e.g. in the case of the Vesuvius area it is about 7-8 km. While to resolve the issue of the polyamide it has been hypothesized to apply the wood-aluminium frame technology in reverse. In fact, it has been placed on the external front of the fixed and mobile frame of the pine wood sections with a thickness of 2 cm with the function of shielding (Fig.10). From the thermal analysis carried out (5), an average temperature of 44°C is recorded for the polyamide elements, considering a time interval of 1200s, only in the case of an agent temperature of 300°C (Fig.11) and therefore the continuity of the sections is preserved.

Table 9 Physical and mechanical properties of Tempered Glass	
Density	2400 [kg/m^3]
Elastic Modulus	70000 [MPa]
Tensile Strength	180 [MPa]
Coefficient of thermal expansion	9 e^{-6} [1/K]
Poisson's ratio	0.23

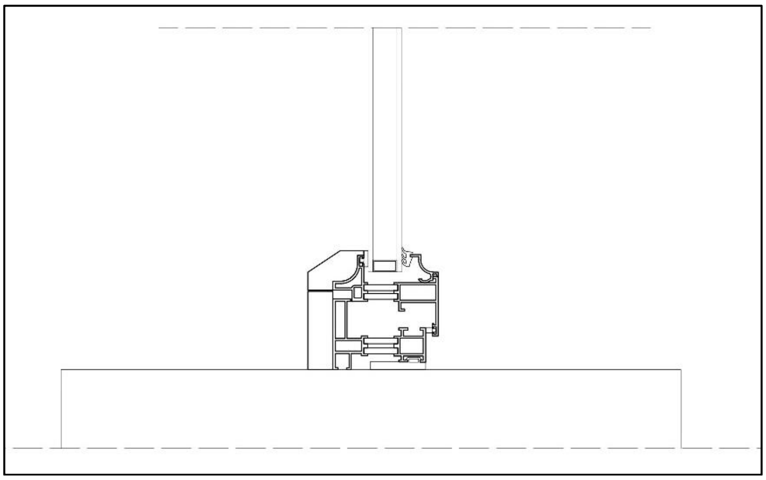

Figure 10. Hypothetical aluminum - wood section.

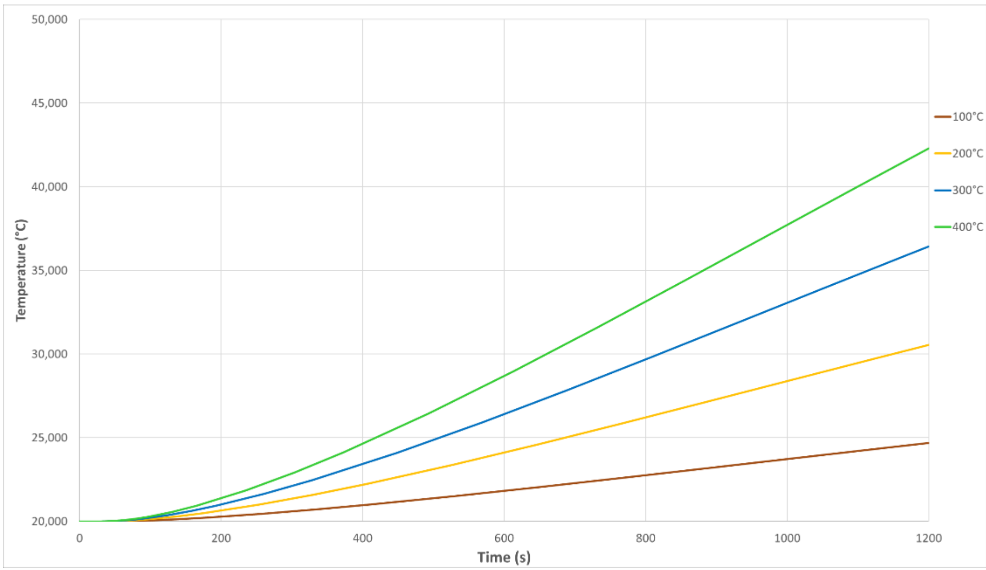

Figure 11. Temperature of Polyamide of Protected Section.

6. Conclusion

The research on mitigation technologies for the reduction of volcanic risk to buildings represents a key field of investigation that is directly connected with the study of volcanic hazard and emergency management. In this context, the definition of possible interventions to reduce the expected damage due to possible eruptions represents a key issue. Through this study, it has been demonstrated that it is not only glass that represents an element of the weakness of the framed system, in fact considering the thermal problem also the other constituent elements such as gaskets and thermal break are a problem to be considered as thermoplastics. Moreover, from these first analyses, it is possible to state that in order to solve the mechanical problem, instead of using laminated glass technology, it is necessary to protect the window frame, the shutters could accomplish this task, and in this case, it is necessary to carry out fluid-dynamic evaluations to identify any infiltration problems or through a sandwich panel, which can withstand both to the expected pressure and the expected temperature; meanwhile, this solution can satisfy the problem of energy saving. Even though the next event is expected to have an intensity lower than a sub-Plinian I, and in this case all the analyses are here designed for a sub-Plinian eruption, would respond more effectively to eruptive phenomena. Nevertheless, in the case of Vesuvius and Campi Flegrei, the main obstacle to the implementation of such measures is the extent of the potentially affected areas, which raises important issues about the economic sustainability of mitigation interventions. Local authorities and private citizens need to be fully aware of the potential damages following an eruption and of the cost-effectiveness of possible mitigation interventions. Considering the economic, political, and social "weight" of volcanic risk in densely populated areas, a valid evaluation method of the effectiveness of mitigation solutions can give scientific support to strategic choices and emergency plans. The approach discussed in the present paper, although about the Vesuvius and Campi Flegrei areas in the specific parameters analyzed (hazard characterization, building typologies, construction technologies), represents a methodology that could also be adopted in other contexts. Further work is being developed to understand the behaviour of shutters considering a fluid dynamic problem and a 3D model of the window to analyze the contribution of further elements such as the hinges and the actual locking system, finally a model in which the mechanical and thermal problem is analyzed simultaneously.

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