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To cite this article: Riccardo Del Bello *et al* 2025 *J. Phys.: Conf. Ser.* **3121** 012033

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Modelling the structural response of Building Integrated Photovoltaic (BIPV) systems in fire

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Abstract. Building integrated photovoltaic (BIPV) systems represent an innovative solution for renewable energy, combining efficiency and sustainability. However, a realistic numerical analysis of the most important phenomena in their multifunctional response is rather challenging. Their structural safety, particularly under fire conditions, requires complex analyses, such as experiments and Finite Element (FE) thermo-mechanical simulations. The objective of this study is to numerically assess the potential of FE predictions for the first glass crack detection (i.e., thermal shock) of a given BIPV in fire, and for the study of the expected structural failure. A numerical parametric analysis is carried out in ABAQUS, considering (as possible influencing parameters superimposed to fire) different glass thicknesses, mechanical restraints, loads. As shown, many critical aspects should be considered in numerical modelling, as well as robust performance indicators are needed. Besides, the FE method could efficiently support the thermo-mechanical analysis and optimisation of BIPVs in fire, and the present study aims at contributing in this direction.

1. Introduction

While BIPVs have well recognised advantages in energy efficiency, the preservation of a sound structural integrity and safety in those extreme conditions that constructions can face, such as fire, remains a critical challenge for them [1]. In general, according to existing standards [2-4], experimental fire tests are carried out on full-scale PV samples to verify the breaking and resisting mechanisms of components, due to extreme temperatures. This is however expensive and challenging, given that tests require financial and technical resources, multiple specimens, and experience for the interpretation of results, which are often hard to be generalised.

In this study, a Finite Element (FE) study is developed in ABAQUS/Standard [5] to preliminary assess the resistance of BIPV systems under extreme temperatures, focusing on the possible detection of the first glass cracking (i.e., thermal shock) and load-bearing structural mechanisms. More in detail, the presented numerical approach is proposed to assess different mechanical configurations of interest for BIPVs in fire, and to emphasize the effect of some key parameters superimposed to fire (glass thickness, mechanical boundaries, mechanical loads), providing a comprehensive understanding of their influence on the overall BIPV response, from a structural/mechanical point of view. The reported findings may contribute to optimising the



design process of BIPVs, for enhanced fire resistance purposes, hence supporting safer and more resilient applications in modern architectures.

2. Modelling strategy

For model calibration and validation purposes, the present study was based on the analysis of a full-scale BIPV sample of literature, which has been tested in [6] in fire (vertical setup). The reference module ($B=1046 \times L=1719$ mm) consisted of a standard sandwich section with two layers of tempered glass ($d=6$ mm thick for each panel, $D=2d=12$ mm the total glass thickness), an Ethylene Vinyl Acetate (EVA) interlayer ($i=1$ mm thick), and embedded monocrystalline solar cells. An aluminium frame was used to secure the edges to the furnace. The experimental protocol imposed a standard time-temperature curve [7] on the exposed BIPV surface.

In this study, a numerical model was developed to simulate the transient thermo-mechanical response of the BIPV tested in [6], and to support some preliminary comparisons. To this aim, according to [8], 8-node 3D elements were used to describe the BIPV components, and two uncoupled analyses were defined for each examined configuration. More in detail:

- A first **thermal model** was used to simulate the temperature distribution over time, due to fire exposure (heat transfer transient analysis). The initial ambient temperature was set in 27°C [6], and the ISO curve [7] was applied on the exposed glass surface.
- A second **mechanical model** was used to assess the structural response (static general analysis). Rigid clamps were applied along the frame, to fix it to the furnace (BC-ALL), and gravitational loads were uniformly distributed. A horizontal pressure q , normal to the unexposed glass surface and kept constant during the analysis, was also considered to assess some further coupled thermo-mechanical indicators for the BIPV system in fire. The nodal temperature in time was imported from the thermal model.

The materials were described in their typical thermo-physical properties, and the calibration approach for glass, EVA and metal fixings followed the assumptions discussed in [9-11]. The embedded solar cells were characterised as in [8]. The selected mesh pattern (with a maximum edge size of solid elements fixed in 5 mm) was designed to provide sufficient accuracy in capturing the instant of thermal shock, and follow the most important structural mechanisms. To reduce the computational cost, however, only one-quarter of the specimen was analysed, applying ideal thermal and mechanical boundary conditions at the symmetry planes, see Figure 1 and [8].

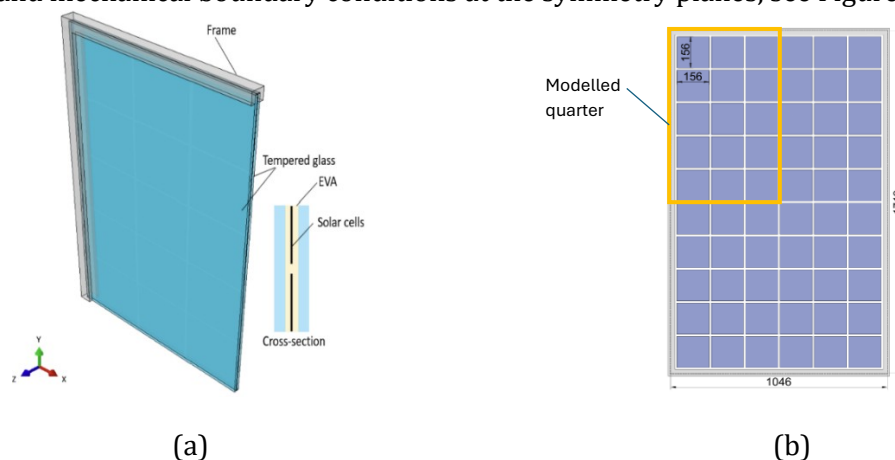


Figure 1. (a) Axonometry of the reference ABAQUS numerical model (67,000 elements and 94,000 DOFs) and (b) geometry of the full-scale BIPV module (dimensions in mm).

The so-assembled reference model, reproducing the specimen tested in [6], was used to conduct a parametric analysis considering the effects of:

- Glass thickness: $d = 6 \text{ mm}$ or 10 mm (corresponding to $D = 12 \text{ mm}$ or $D = 20 \text{ mm}$)
- Mechanical loads superimposed to fire: $q = 0, 500, 1000,$ or 2000 Pa .
- Mechanical boundaries: **full perimeter constraint (BC-ALL)**, corresponding to vertical and horizontal edges restrained; **lateral constraint (BC-SIDE)** with vertical restraints only; **upper-lower constraint (BC-UP)** with horizontal restraints only.

The experimental setup from [6] corresponded to the herein labelled BC-ALL configuration, with $d = 6 \text{ mm}$ for each glass panel and no additional mechanical loads ($q = 0$).

3. Failure criteria

In general, the evaluation of resistance and failure mechanisms for a given building system must consider multiple factors. For BIPVs, while the primary concern is typically represented by the first failure of the exposed glass cover, other components may also be affected by temperature increase, and hence produce severe impact on the overall system performance.

A practical and widely used method for detecting the onset of glass cracking relies on monitoring thermal differences between the hottest and coldest areas of the panel [12-14]. For tempered glass, the allowable thermal difference is set in $\Delta T_{allowable} = 200^\circ\text{C}$, while the allowable thermal stress is $\sigma_{t,allowable} = 116.20 \text{ MPa}$. Additional performance indicators (including those outlined in [15] for fire exposed construction components) were also considered in this study, particularly referring to indicators for structural elements in bending:

- Maximum deformation (out-of-plane displacement): $C = L^2 / (400 \cdot D)$
- Maximum deflection rate: $dC/dt = L^2 / (9000 \cdot D)$

where L is the largest dimension of the panel and D the thickness of both glass layers, in mm. For the reference BIPVs, the maximum deformation value was calculated in **615 mm** and **369 mm** (for the $D = 6+6 \text{ mm}$ and $10+10 \text{ mm}$ configurations), with a maximum deflection rate of **27 mm/min** and **16 mm/min** respectively.

4. Results and discussion

From a first analysis of numerical estimates, the comparative results indicate that the crack initiation time in the exposed glass cover can largely depend both on the mechanical boundaries of the BIPV system (Figure 2(a)) and the thickness of glass (Figure 2(b)).

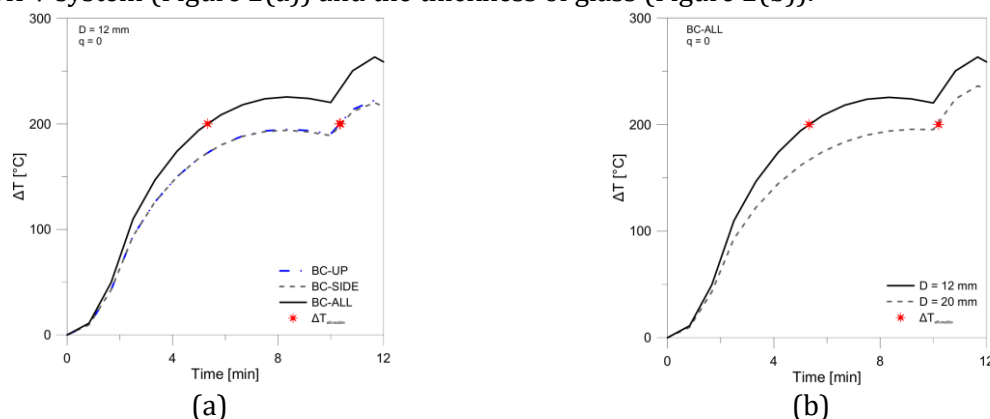


Figure 2. Temperature difference between the hottest and the coldest region of the exposed glass panel, for the BIPV system with different (a) mechanical boundaries and (b) glass thicknesses (BC-ALL).

For the reference module ($D=12\text{ mm}$, BC-ALL, $q=0$), the first cracks were predicted to appear after $5'20''$ of fire exposure, which well agrees with the experimental outcomes ($\approx 6'$) discussed in [6], considering the model simplifications. Additional validation and calibration is reported in [8]. Increasing the glass thickness to $D=20\text{ mm}$ can enhance the failure time of the BIPV system up to $\approx 10'$. It is important to note, however, that this failure time was exclusively assessed based on the temperature criterion (Section 3), which varies according to mechanical boundaries only. Specifically, for BC-ALL, the exposed glass surface is smaller than BC-SIDE and BC-UP configurations, as it can be seen from Figure 3. This aspect affects the crack initiation time and leads to a higher thermal difference on the glass cover, thus to possible premature failure.

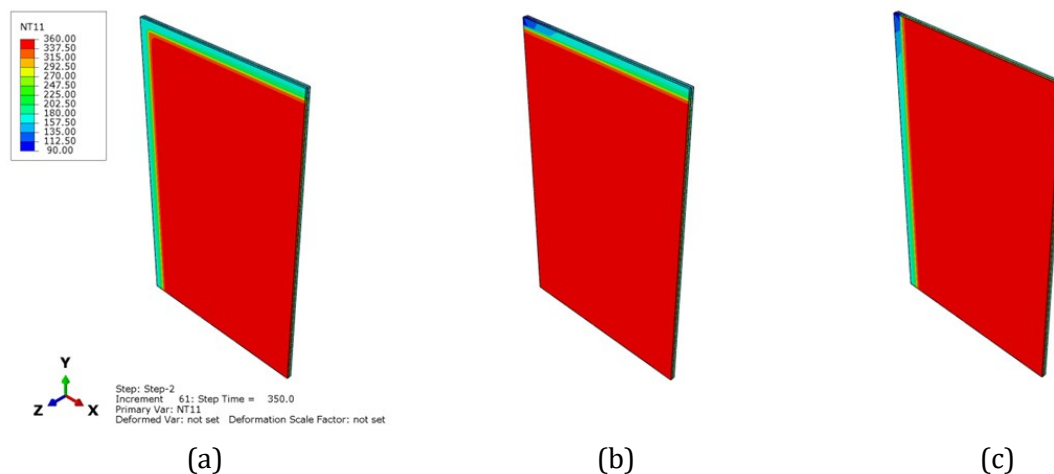


Figure 3. Temperature on the exposed glass panel close to failure, based on the allowable temperature difference ($D=12\text{ mm}$, $q=0$): (a) BC-ALL, (b) BC-UP and (c) BC-SIDE configurations (legend in $^{\circ}\text{C}$).

Regarding the corresponding stress evolution in glass, the analysis of results showed that there is no significant difference in the examined configurations. However, it is also important to note that the maximum stress was generally achieved in the unexposed glass panel, in the coldest and stiffest regions (Figure 4(a)). After about $\approx 2'25''$ – $2'40''$ of fire exposure, see Figure 4(a), the stress peak generally exceeded the allowable value (thus before the exceedance of the thermal failure criterion on the exposed glass panel at about $5'20''$). The same effect was noticed for most of the examined configurations (Figure 4(b)). This aspect suggests to pay attention on the possible occurrence of premature cracks in the unexposed glass panel, especially close to restraints (Figure 4(a)), and that this phenomenon should be properly taken into account for safety assessment.

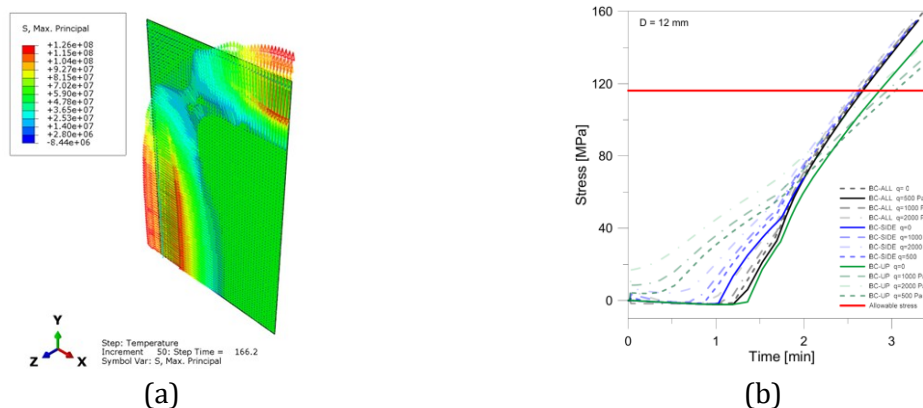


Figure 4. Stress analysis in the unexposed glass panel: (a) typical distribution (example for $D=12\text{ mm}$, BC-ALL, $q=0$, at the first exceedance of the allowable stress; legend in Pa), and (b) maximum principal stress trends in time.

The displacement analysis revealed a typical nonlinear behaviour for the examined BIPVs, with a marked effect of thermo-mechanical phenomena. By examining the maximum out-of-plane displacement at the centre of the BIPV systems (Figure 5), it was for example observed that the consequences of mechanical loads q (if any) are dominant for a certain time interval and restraint condition only, compared to the consequences of fire. However, as the temperature increases, the thermal deformation rapidly prevails on the deflection from pure mechanical loads, and also reduces the bending stiffness of the BIPV system, due to heating and material degradation [9]. The stress peaks, accordingly, also migrate to the coldest regions (i.e., Figure 4(a)).

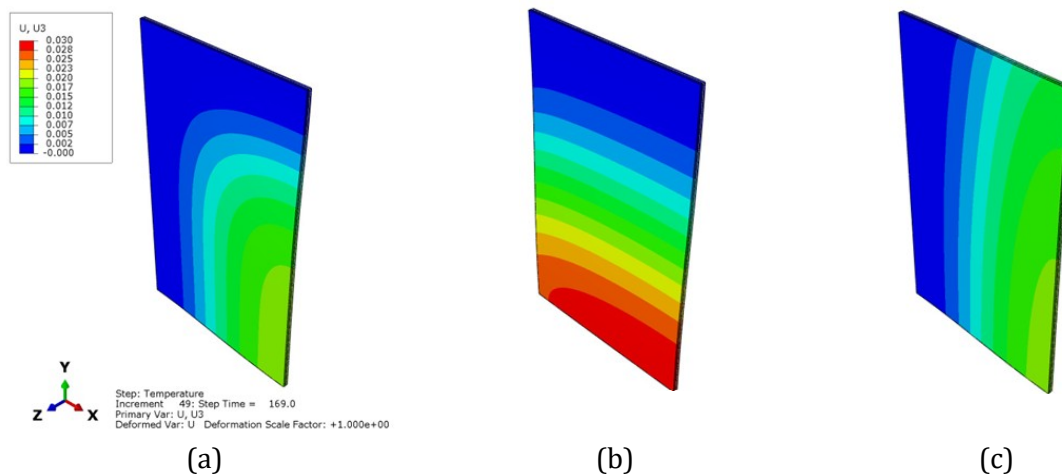


Figure 5. Example of out-of-plane displacement for the BIPV system with $D=12$ mm, $q=500$ Pa and different restraints: (a) BC-ALL, (b) BC-UP and (c) BC-SIDE configurations at the instant of exceedance of the allowable stress in glass (legend in m).

Overall, the most significant effects were found to derive from the panel geometry (i.e., glass thickness) and restraints (i.e., degree of restraint at the edges). BIPVs restrained as in BC-UP layout exhibited greater deformation, and a delay in the predicted instant of thermal failure, whereas panels restrained only laterally (BC-SIDE) reached more quickly the failure stress threshold. Nevertheless, none of them approached the critical deflection limit calculated as in [15] and Section 3. Considering the deflection rate ([15] and Section 3), none of the configurations exceeded the limit, with the exception of a single setup. This is emphasised in Figure 6 by the red star, for $D=20$ mm. The calculated parameter exceeded the threshold after 2' 25", indicating that a critical condition for failure may initiate earlier than expected, compared to severe temperatures or stress peaks. Besides, specific limit values should be defined and calibrated for BIPV systems.

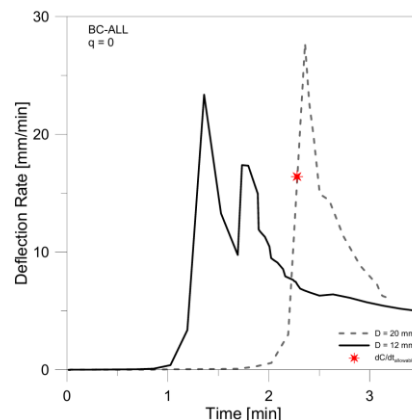


Figure 6. Example of deflection rate for $D=12$ mm and 20 mm configurations (BC-ALL, with $q=0$).

5. Conclusions

Fire safety assessment of BIPVs is challenging, for several reasons. Numerical methods, in this regard, can support a detailed analysis of their performance but require sound calibration of model components, as well as robust performance indicators. The present parametric study, in this sense, preliminarily demonstrated that the structural safety of BIPVs in fire depends on multiple factors and thermo-mechanical interactions. The numerical analysis, in particular, provided valuable insights for investigating further the resisting mechanisms of BIPVs in fire and support their optimal structural design. The use of optimised glass thickness and restraints for a given size, for example, could strongly enhance the overall response, reducing the risk of premature failure. Future research will be carried out in this direction.

Acknowledgments

This study was carried out in the framework of the ongoing “3FiRES” Particular Relevance Italy-China bilateral project “Research on BIPV Photovoltaic Facades for Fire Spread Mechanisms, Structural Failures and Resilience Improvement Methodologies” (2024-2025). The work was supported by the National Key R&D Program of China (2023YFE0116700) and the Italian Ministry of Foreign Affairs and International Cooperation (CN24GR03).

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