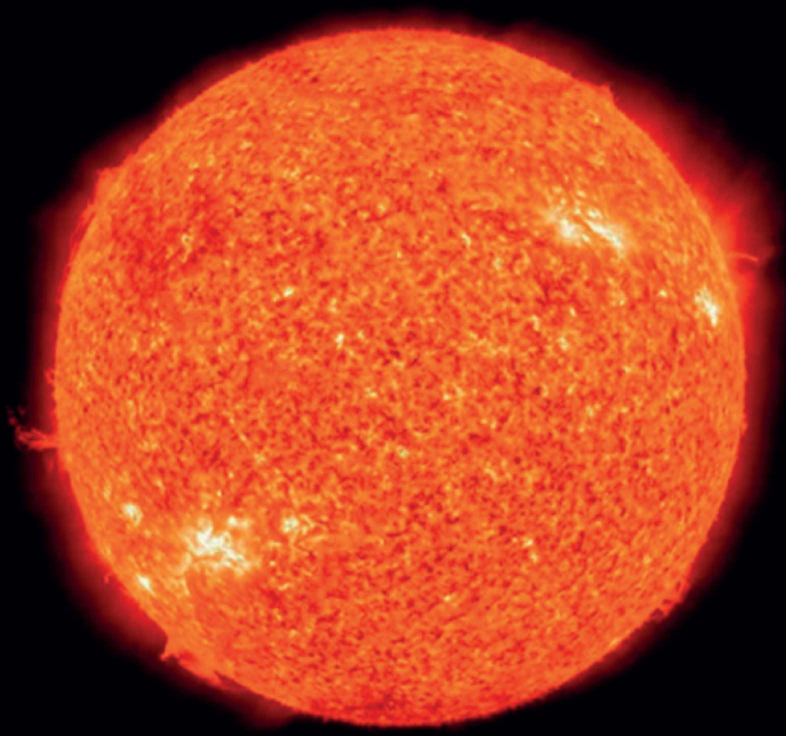

First-year 3FiRES Booklet

• Workshop and network updates about • Research on BIPV Photovoltaic Facades for Fire Spread Mechanisms, Structural Failures and Resilience Improvement Methodologies • edited by Chiara Bedon & Yu Wang •

[…] There are no doubts that the first-year of scientific activities for the running 3FiRES project represented a powerful opportunity of scientific network and growth for the members of research units on both the Italian and Chinese sides, as well as a unique international experience to share methodologies and discuss new strategies for the analysis of BIPV components and facades in fire […]
Chiara Bedon, Yu Wang

[…] Talking about the optimization of novel prototypes, for example, robust standardized methodologies of experimental investigation are of utmost importance. However, the same consideration can be extended to in-service plants, where efficient diagnostic strategies have a primary role for the analysis of photovoltaic components and systems, both under ordinary and accidental operational conditions. […]
Chiara Bedon, Yu Wang

[…] solar energy has become part of the building fabric as a sustainable alternative, and then it has become obligatory and, today, increasingly indispensable. This is a great opportunity for architectural, urban and landscape design, but let us not forget that when we use and transform this technological device in architecture, solar is synonymous with happiness and beauty […]
Adriano Venudo

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Workshop and network updates about "Research on BIPV Photovoltaic Facades for Fire Spread Mechanisms, Structural Failures and Resilience Improvement Methodologies"

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This volume collects some scientific research results from the first year of activities and Workshop contributions (October 7th, 2024, Trieste & online) of the running "Particular Relevance" Italy-China bilateral project 3FiRES - "Research on BIPV Photovoltaic Facades for Fire Spread Mechanisms, Structural Failures and Resilience Improvement Methodologies" (2024-2025). 3FiRES research partners are the University of Trieste, Department of Engineering and Architecture (Principal Investigator Prof. Chiara Bedon) and University of Science and Technology of China, State Key Laboratory of Fire Science (Principal Investigator Prof. Yu Wang). The scientific activities of 3FiRES project are partly financially supported by the Italian Ministry of Foreign Affairs and International Cooperation (grant number CN24GR03) and National Key R&D Program of China (grant number 2023YFE0116700).

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Simulating the thermo-mechanical failure of glass-glass building-integrated photovoltaics in fire

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Abstract
Modelling the complex phenomena that take place in the multifunctional response of building-integrated photovoltaics (BIPV) is a rather challenging task. Moreover, several operational conditions can take place and represent additional influencing parameters for material properties and performances. As such, specific performance indicators are required to assess the mechanical capacity, resisting mechanisms and failure occurrence of these composite systems, both under ordinary or extreme design actions. Part of the running 3FiRES research activity deals on the development and validation of efficient numerical models that could be used – for a general scenario – to track and capture the thermo-mechanical performance and failure of BIPVs in fire. This contribution summarizes some important aspects that should be taken into account for a robust analysis. The target, as shown, is a commercial glass-glass BIPV system subjected to the simultaneous action of thermal (i.e., time-temperature conventional fire) and mechanical loads.

Keywords
Building-integrated photovoltaics; fire safety; failure mechanism; numerical modelling.

Introduction

The numerical simulation of failure mechanisms for structural components and systems is often challenging, and for specific materials requires a careful consideration in calibration, validation, interpretation and assessment. Building-integrated photovoltaics (BIPV), and their resisting mechanisms under operational conditions, are particularly challenging because of the mutual interaction of materials and components that are part of the resisting sandwich section. Even more uncertainties are faced in their analysis under extreme design actions, such as fire [01].

The present research study, which is part of the running 3FiRES project, focuses on the refined numerical analysis of BIPVs in fire, and on the definition of a robust numerical approach to predict their failure in fire.

Reference system and numerical modelling

The reference BIPV is the same full-scale specimen explored in “Progress on numerical simulations for thermal shock prediction of glass-glass BIPVs in fire”, see Figure 1. The difference is represented by a primary attention for coupled thermo-mechanical resisting and failure mechanisms.

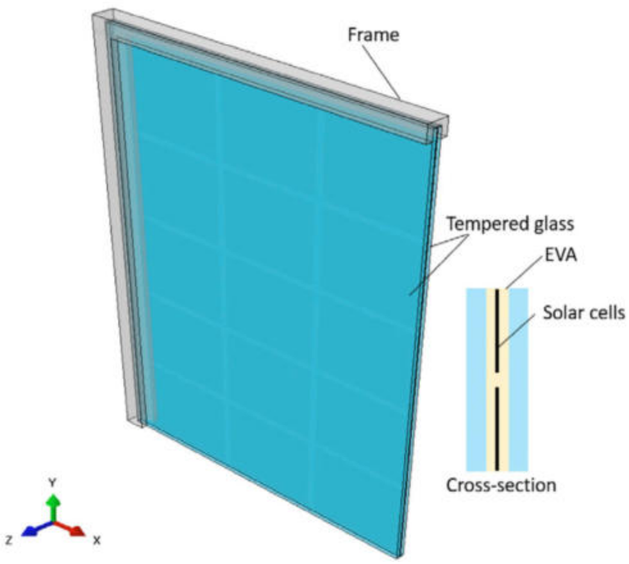

Figure 1.
Axonometry of the reference numerical model (ABAQUS).

To this aim, a reference FE model is developed in ABAQUS [02]. The attention is given to the use of a subsequential simulation procedure, in which a “static general” analysis is carried out to combine the analysis of mechanical loads with the previously performed thermal stage, which is imported as reference temperature in time for all the mesh elements and nodes. Such a solving strategy for combined thermo-mechanical mechanisms is in line with past experiences and applications to structural glass components and systems in fire [03-05].

Analysis, performance indicators and results

The analysis of resisting and failure mechanisms for BIPVs subjected to fire and possible mechanical loads should take into account multiple aspects, that are typically associated to the possible failure of the covering glass plates, but can also affect the other BIPV components (and thus negatively impact on the final performance of the system).

For the present study, the reference BIPV prototype, was analysed with a careful attention for multiple performance indicators of typical use in practice. The listed performance indicators, in particular, were considered for thermo-mechanical assessment of similar systems, in terms of most severe indicator and prevailing failure mechanism. The latter is in fact a complex condition to estimate, since it depends on a multitude of influencing factors (geometry, materials, loading time, thermal exposure, etc.). The maximum effects of fire (and the corresponding possible failure) were thus numerically detected as the most conservative of four different indicators, in terms of:

- “Temperature approach”: the measured thermal gradient between the exposed and coldest regions of glass was compared to the reference limit values, see [06-08] and Table 1. The corresponding failure time was expressed as:

$$t_{f,temp} = t(\, \Delta T \geq \Delta T_{all}) \quad (1)$$

- “Stress approach”: the resulting thermal stress peaks in tension ($\sigma_{max,t}$) and the superimposed mechanical stress peaks ($\sigma_{max,m}$) were compared with the nominal allowable thermal stresses of Table 1, which notably is lower than the characteristic material strength at room temperature (120 MPa for tempered glass). Accordingly, to detect collapse, the failure time $t_{f,stress}$ for stress peaks was calculated as:

$$t_{f,stress} = t\left(\frac{\sigma_{max,t}+\sigma_{max,m}}{\sigma_{t,all}} \geq 1\right) \quad (2)$$

Table 1. *Allowable thermal gradients (ΔT_{all}) for glass, and corresponding stresses ($\sigma_{t,all}$) for fully-tempered glass* [06].

	Edges		
	As-Cut or Arrised	**Smooth Ground**	**Polished**
Temperature [°C]		200	
Stress [MPa]		116.20	

Additional relevant performance indicators could be taken into account to detect the possible failure time of glass.
In this study, for example, the EN-1363-1 standard [09] was considered, as it proposes conventional limit values for structural components in fire. When the elements are "mainly loaded in bending":

- maximum deformation (out-of-plane displacement):

$$C = \frac{L^2}{400\,d} = \frac{1700^2}{400 \times 12} = 602\,mm \quad (3)$$

- maximum deflection-rate:

$$\frac{dC}{dt} = \frac{L^2}{9000\,d} = \frac{1700^2}{9000 \times 12} = 26.75\,mm/\text{min} \quad (4)$$

For elements under "in-plane" loading:

- maximum deformation (in-plane displacement):

$$C = \frac{L}{100} = \frac{1700}{100} = 17\,mm \quad (5)$$

- maximum deflection-rate:

$$\frac{dC}{dt} = \frac{3L}{1000} = \frac{5100}{1000} = 5.1\ mm/\text{min} \qquad (6)$$

In Eqs. (3)-(6), L= 1700 mm is the span and d= 12 mm denotes the thickness of the examined structural component.

Typical results from the numerical analysis are reported in Figure 2, for the examined BIPV under standard fire (self-weight included). The attention is given to tensile stress peak in glass (which are notably first achieved in the unexposed

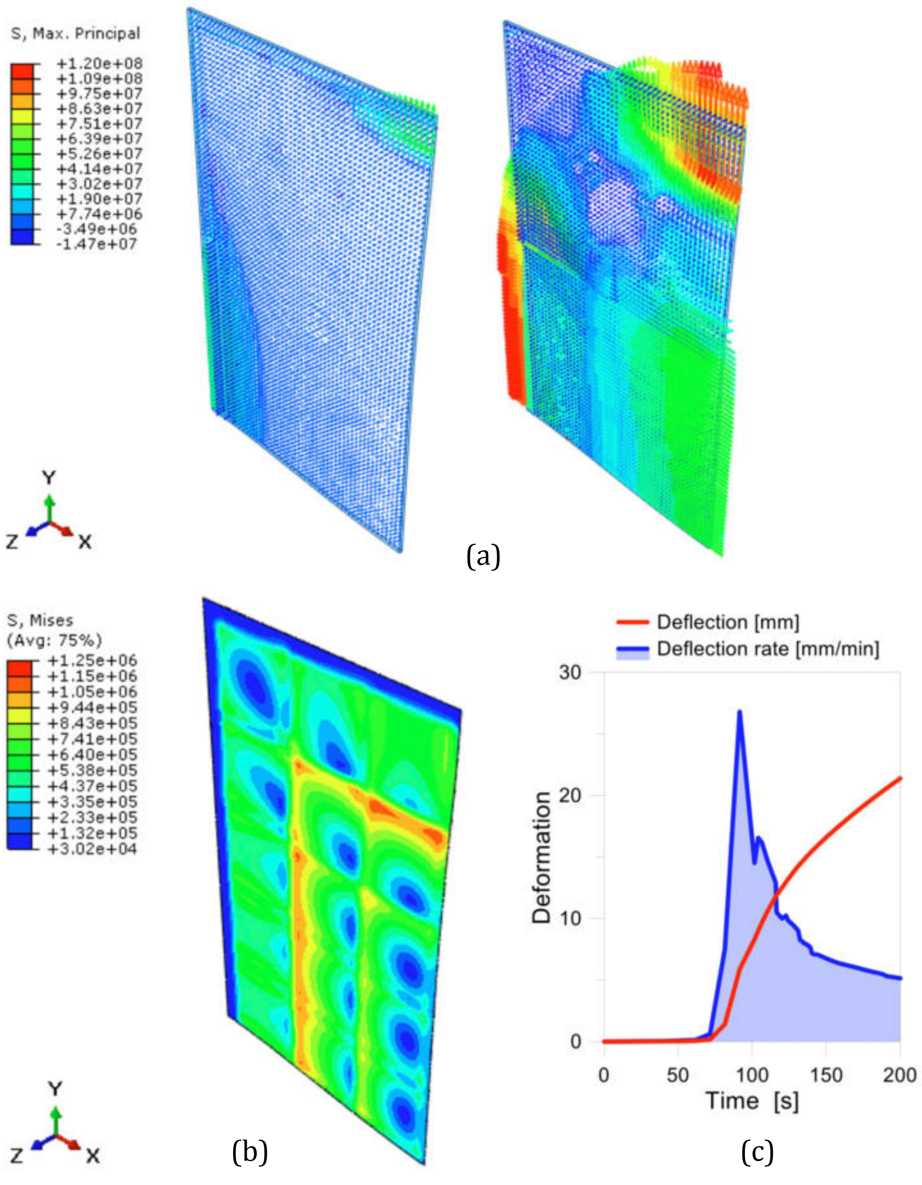

Figure 2. *Typical numerical results of the thermo-mechanical analysis (ABAQUS): (a) tensile stress in the exposed and unexposed glass panels; (b) Von Mises stress in the encapsulant; (c) deflection and deflection rate in time (out-of-plane).*

panel, at about 2’ 45’’ of fire exposure (Figure 2(a)), on the limited and non-uniform stress distribution in EVA (Figure 2(b)), as well as to deformation aspects (Figure 2(c)). The effect of temperature increase can be noted in the non-uniform spread of stress peaks in glass, and also in Figure 2(c), in the drop after about 2’ of fire exposure. However, it is also worth to note that the exposed glass panel (exceeding the allowable thermal gradient and suffering for experimental thermal shock after ≈6’) shows in time tensile stress peaks that are significantly lower than the unexposed (and coldest) glass layer. This effect depends on the influence of non-uniform temperature spreads and on the additional influence of boundaries, thus requiring further extended studies.

Conclusions and future steps

The summarized numerical results highlighted that the thermo-mechanical failure analysis and detection in BIPVs is a rather challenging task, especially in numerical terms. The proposed multi-target approach for modelling and failure assessment could represent a possible basis for generalized use in the analysis of BIPVs under fire and mechanical loads.

In the present study, the attention was given to the detection of existing performance indicators that are of typical use (in different fields) and find a direct application for the assessment of glass-glass failure mechanisms. Besides, the reported results highlighted that most of existing conventional limit values (of robust validation for different structural components) are not directly applicable to glass-glass BIPVs, and require a specific calibration to capture the most important and critical phenomena. Moreover, future experimental tests that are presently in preparation for 3FiRES activities will be necessarily required for the optimal calibration of a robust numerical strategy.

Acknowledgements

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Figures 3-4. *Experiments on a glass-glass BIPV roof at University of Trieste,* Department of Engineering and Architecture (photo © Nicola Blasuttigh), specimens manufactured by MrWATT.