Impact damage identification in GFRP structures using the effective boundary approach

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Abstract: Heat accumulation during the non-uniform thermal excitation with a halogen lamp presents a significant challenge in detecting low-velocity impact damage (LVID) of composite plates. This accumulation reduces the temperature contrast between damaged and undamaged areas in the thermograms, making LVID identification more difficult. To tackle this issue, this study utilized the concept of the boundary of effective thermograms (BET) to determine the optimal sequence of registered thermograms, which were subsequently analyzed using the partial least squares regression (PLSR) image processing algorithm to enhance damage identification.

1. Introduction

The growing reliance on composite structures, including glass fiber-reinforced polymer (GFRP), in various engineering sectors, including aerospace, automotive, and marine industries, is driven by their outstanding mechanical properties, such as high strength-to-weight ratio highlights the need for design adaptability. However, these structures are susceptible to low-velocity impact damage (LVID), which can significantly compromise their structural integrity and operational lifespan. Among the various non-destructive testing (NDT) techniques, halogen lamp-based thermography is still employed for assessing impact damage due to its rapid inspection capabilities and non-contact operation.

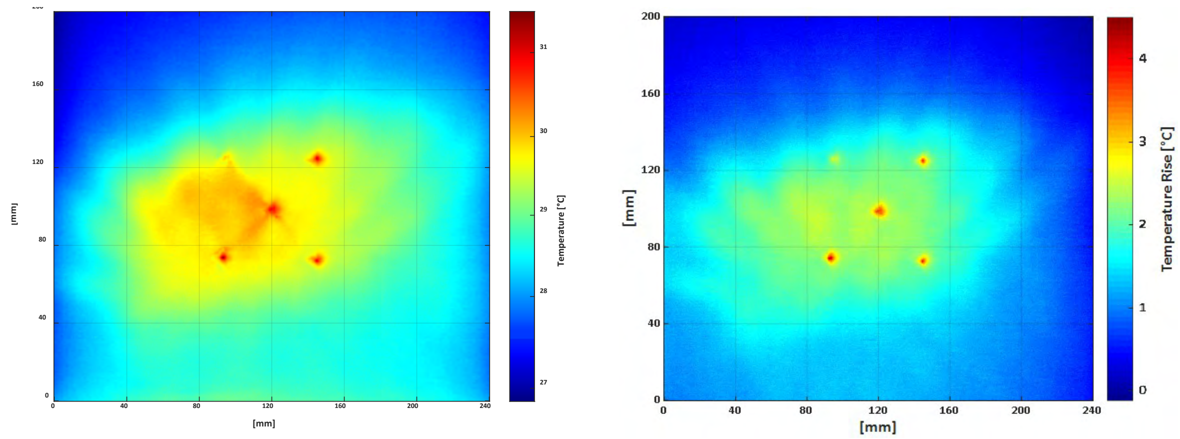
2. Specimen and testing procedure

The GFRP plate used in this study was fabricated from E-glass fiber-reinforced epoxy composite material, comprising six layers of plain weave fabric with an areal density of 200 g/m², supplied by Izo-Erg S.A. (Gliwice, Poland). The similar mechanical properties of the plain weave reinforcement in two directions allow for the elimination of the effect of fiber orientation on the impact-induced response. The dimensions of the tested GFRP are presented in [1]. To simulate LVID, a custom-designed drop-weight impact test machine was employed [2]. The impactor, labeled as E (see [2] for details), was selected to introduce multiple LVIDs in the GFRP plate. An energy level of 7 J was applied using this impactor. A total of five LVIDs were introduced, with the first impact at the center of the GFRP plate. The remaining four impacts were introduced at the corners of a 50 mm × 50 mm square, positioned 25 mm from the center along both the horizontal and vertical axes, within the center of the 200 mm × 240 mm plate.

The testing procedure for evaluating multiple LVIDs in the GFRP plate involved using a continuous halogen lamp (1 kW), model PLC64AL by Proel S.p.a., as the thermal excitation source. The thermal response of the GFRP plate was captured with an IR camera, Titanium by Cedip FLIR LLC, equipped with a cooled InSb sensor having a noise equivalent temperature difference (NETD) of less than 25 mK. The camera recorded thermal transients on the surface of the GFRP plate for approximately 10 seconds at a frame rate of 15 Hz.

3. Results

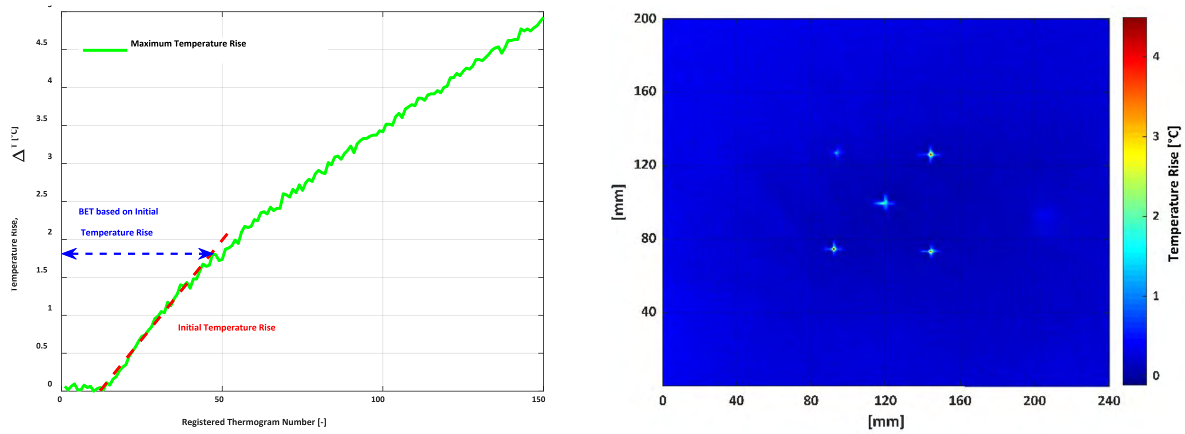
The registered thermogram captured after 10 seconds of testing, shown in Fig. 1(a), reveals the challenges inherent in halogen lamp-based thermography. Heat accumulation within the GFRP plate caused by the non-uniform thermal excitation from the halogen lamp resulted in a reduced temperature contrast between damaged and undamaged regions. This heat spread across the GFRP surface, diminishing the sensitivity of the technique and complicating the identification of LVIDs. Additionally, environmental factors may further influence the accuracy of the thermal imaging, leading to blurred thermograms. To mitigate this, the thermal response corresponding to the initial condition of the test was subtracted from the registered IR image at the end of testing. The subtracted result is shown in Fig. 1(b). This normalization process allowed for the elimination of thermal noise and environmental influences, thereby making it easier to highlight the damage-induced temperature changes. However, reliance on the raw thermal images, even after normalization, still poses a risk of misinterpreting the extent and location of the LVIDs.



(a) (b)

Fig. 1. Registered raw thermogram after 10 sec: (a) before normalization, (b) after normalization.

To enhance the identification of LVIDs, this study implemented the BET concept, a method that determines the optimal sequence of thermograms for identifying LVID in the GFRP plate. Similar to the previously published approach [2], the BET was established at the initial stage of the test, during which the maximum temperature gradient occurred. This dynamic parameter serves as an indicator of the period in which the GFRP plate experiences the highest heat transfer over a short time interval. Fig. 2(a) illustrates the maximum temperature rise observed on the surface of the GFRP plate during testing. The BET was selected by fitting a linear regression to the thermal response curve, and the thermogram corresponding to the point of tangency with this regression line was identified as the optimal BET. These selected thermograms were then analyzed using the PLSR algorithm in MATLAB software. The result of this image processing is depicted in Fig. 2(b), where the enhanced thermogram distinctly differentiates between damaged and undamaged areas, improving the reliability of LVID identification.



(a) (b)

Fig. 2. (a) Optimal BET determined via the initial temperature rise, (b) Enhanced thermogram obtained from BET-based PLSR image processing algorithm.

4. Conclusions

This study demonstrated the challenges of using halogen lamp-based thermography to identify LVIDs in the GFRP plate, primarily due to heat accumulation and environmental influences. Utilizing the BET approach alongside PLSR-based image processing improved the temperature contrast, leading to better identification of LVIDs.

5. Acknowledgements

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References

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