Application of Digital Image Correlation to Structures in Fire

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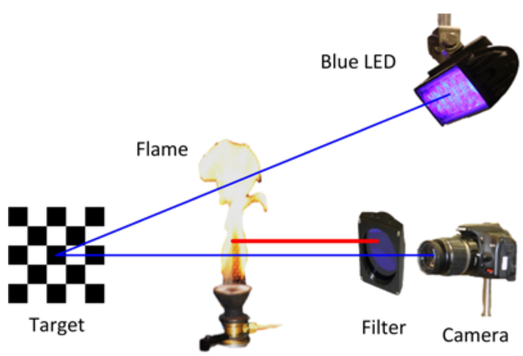
1 Introduction

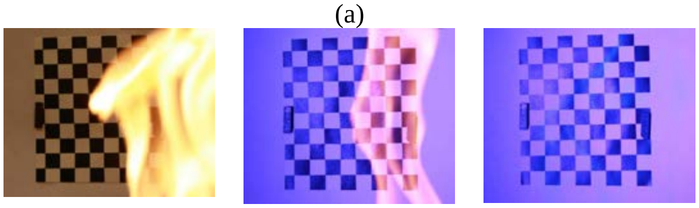
The behavior of engineering structures in fire is commonly studied through large-scale experiments. However, temperature-varying material properties, spatially-varying thermal loading and complicated structure geometries result in these structures deforming in complex and often unpredictable ways. This makes it difficult to fully characterize the response of the structure with traditional (point) sensors [1]. Full-field, noncontact measurement techniques such as Digital Image Correlation (DIC) are potentially ideal for such experiments; however, the presence of light emitted by the flames, thermal radiation from the heated structure, and convective thermal gradients in the air make this a challenging application for DIC.

2 Imaging Through Fire Using Narrow-Spectrum Illumination

A simple and robust method has been developed to enable the use of DIC in large, low-soot, fires to measure targets at temperatures up to 800 °C. This method, which builds on work by Grant [2] and Pan [3], uses narrow-spectrum blue light (450 nm ±10 nm at one standard deviation) and spectrally-matched band-pass optical filters to increase signal-to-noise ratio and filter undesired radiant energy before it reaches the camera [4]. Fig. 1a shows a benchtop-scale demonstration of this method. The distance from the camera to the target is about 1 m. Fig. 1b contains three images of the same natural gas flame with different illumination and filtering methods applied. In the image on the left, no filters are used, and the target is illuminated only by the flame and ambient lighting in the room. In the middle image, a 10 W 450 nm light emitting diode (LED) source is added to illuminate the target; improving the visibility of the target. In the image on the right, a band-pass optical filter is placed in front of the camera, blocking the light from the flame and allowing the target behind the flame to be seen clearly. This technique can reduce the observed intensity of the flame by a factor of 10^4, which is sufficient to image full-scale structural experiments using less than 50 W of applied illumination [4].



(a)



(bi) (bii) (biii)

Fig. 1 Demonstration of imaging method: (a) schematic of setup and (b) target viewed through 5 kW natural gas flame when illuminated with i) ambient light, ii) 10 W of 450 nm light, and iii) 10 W of 450 nm light and imaged through a band-pass filter.

3 Applications to Optical Metrology

The proposed filtering method allows DIC measurements to be made through flames that have low soot content. Converting the images to quantitative measurements poses additional challenges because the gas temperature gradients optically distort the images causing fictitious (apparent) strains. While there is a steady-state aspect of this distortion caused by the overall shape of the fire, in a large diffusion flame, the turbulent flow (flicker) of the flame is responsible for most of the distortion. The characteristic frequency of the flame flicker is on the order of ~10 Hz at the small scale [5, 6], and lower frequency transient distortions can occur due to variations fire ventilation at the large (1 m) scale. Meanwhile the characteristic dimension of individual flame eddies is on the order of 5 cm. As the strain rates in structural testing are slow relative to the flame motion, temporal and spatial averaging can be used to improve the accuracy of measurements.

4 Application to Full-Scale Experiments

The method described above was applied to several repeated full-scale experiments in which a 6 m long W16×26 steel beam was supported over a 700 kW fire from a natural gas diffusion burner (Fig. 2a). Measured gas temperatures in the flame exceeded 1400 °C and the steel beam reached temperatures over 700 °C [7]. A commercial DIC system, with optical filters installed, was placed at 3 m stand-off and the specimen was illuminated using two 100 W blue LED arrays. The target area was approximately 0.4 m high by 1 m long. Prior to painting a pattern to enable DIC, the surface oxide layer ('mill scale') on the beam was removed using sandblasting, as it naturally flakes off when heated above 400 ºC or when the steel yields. A base layer of white high-temperature spray paint was applied followed by a random pattern stenciled in black spray paint to provide contrast (Fig. 2a). The combination of a white base coat with a black pattern was found to be more temperature-resistant than the inverse. The optical distortion from the flame, and necessary time averaging, have the effect of blurring the image to be processed with DIC, so the pattern was designed to be coarser (10-20 pixels/feature) than necessary in an unobstructed test (3-5 pixels/feature).

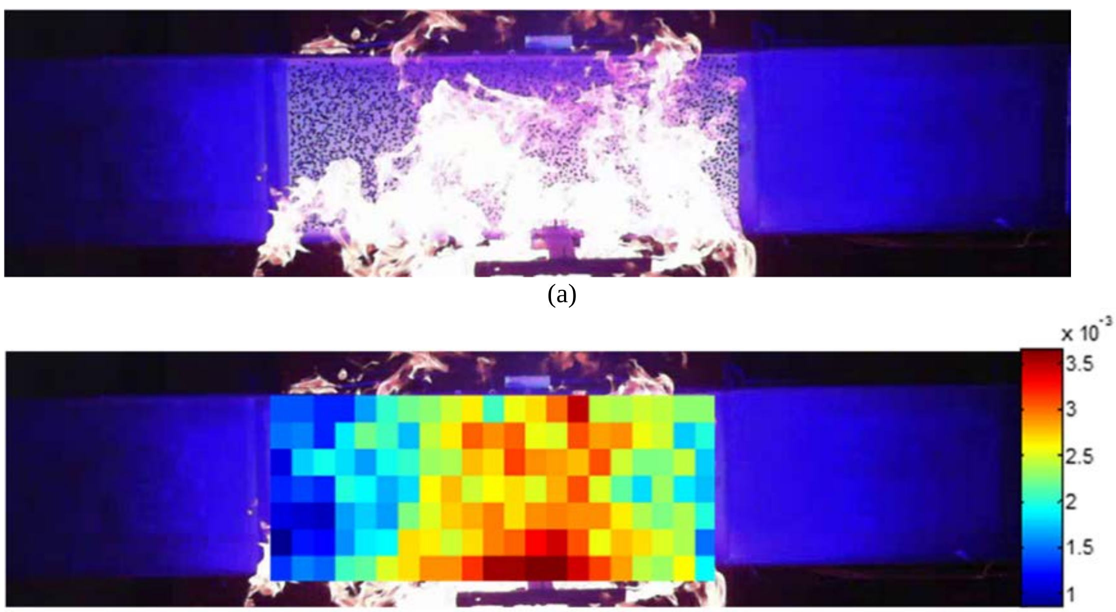


Fig. 2 Full-scale validation tests: (a) test setup and (b) example of measured longitudinal strain field (units in mm/mm).

During the experiment, the beam was heated by the flame, and the thermal strains were measured using DIC. Images were recorded at 1 Hz and time-averaged over 30 seconds to remove transient flame effects. The time-averaging was performed on the raw images, which were subsequently reimported into the DIC system for processing. After performing the DIC, the resulting strains were spatially averaged over 4 cm regions (100 pixels). As illustrated in Fig 2b, this method was sufficient to differentiate thermal strains in the steel of 3 microstrain from the flame-induced distortion. The tests also suggest that time averaging is preferable to spatial averaging, at least for structural experiments for which spatial resolution is preferable to temporal resolution. Further work is needed to better understand the post-processing options and methods for this application and to quantify the uncertainty associated with these processes.

5 Conclusions

Noncontact measurement techniques, such as Digital Image Correlation (DIC), are desirable for use in structural fire experiments because deformation and failure in large structures subject to fire is often unpredictable. The presence of light emitted by flames, thermal radiation from the heated structure, and convective thermal gradients in the air have challenged the use of DIC. A simple and inexpensive method to improve the signal-to-noise ratio (10^4 compared to ambient lighting) in images of objects taken through low soot-yield fires is described and has been successfully deployed on large scale fire tests. The resulting images were temporally and spatially averaged during post-processing to smooth out false distortions of the images caused by the thermal gradients in and around the flames before DIC techniques were applied to resolve strain. Additional work to quantify the uncertainty associated with these processes is needed.

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