**RESOLVING OBSTRUCTED VIEWS USING MULTIPLE THERMOGRAPHY DIGITAL IMAGE CORRELATION SYSTEMS**

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**ABSTRACT**

Full-field measurements of the thermal and displacement response of a stiffened aluminium plate subjected to combined compression loading and one-sided heat flux were obtained using a fused thermography digital image correlation (TDIC). One limitation of this method with a single TDIC system is the inability to measure complex shapes where portions of the sample are obscured from the cameras’ view. By stitching measurements from two TDIC systems together using a rigid body transform, measurements were obtained which reduced the effects of this limitation. The obtained temperature and displacement measurements were subsequently used as validation for finite element (FE) simulations.

**INTRODUCTION**

Full-field measurements of the thermal and displacement response are needed to quantify behavior of complex elements or structures during fire scenarios. Typically, these are obtained using an array of point measurements obtained from sensors such as thermocouples or string potentiometers. However, from a practical viewpoint, it can be difficult to attach these sensors without affecting the sample. Additionally, the selection of points for instrumentation on complex elements or structures where the failure location is uncertain *a priori* and the spatial distribution in the response varies widely can be difficult. The use of non-contact measurement methods reduces the effects of instrumentation on the sample and has the potential to allow full-field measurements on a surface.

One recently developed non-contact method for simultaneously obtaining full-field thermal and displacement responses is thermography digital image correlation (TDIC).1 The TDIC method utilizes a pair of stereoscopic charge-coupled device (CCD) digital cameras and one infrared (IR) camera normal to a surface to measure full-field 3D deformation and temperature. Through the coupled calibration procedure, the temperature and deflection measurements are mapped to the same coordinate system, which has the benefit of tracking temperatures with the deforming structure1. To date TDIC has been used for high temperature composite testing1-2, open fire testing of structural elements3, and burn-through testing of marine grade aluminum structural plates.4

TDIC measurements in previous studies have been limited to a single surface due to limitations on camera field of view and obstruction of the sample. However, mechanically tested elements and structures are three dimensional in nature, and often it is desirable to obtain measurements on multiple surfaces. One way to bypass this limitation is to obtain measurements from multiple TDIC systems and develop a coordinate transform between the systems to map the measurements to the same coordinate system. This paper presents results from using two separate TDIC imaging systems to make measurements on a plate with T-stiffeners exposed to a constant heat flux while being subjected to mechanical load. A calibration technique is presented that allows for the results from the two systems to be stitched together, forming a spatial and time synchronized result on multiple surfaces. The measurements are compared with computational results.

**EXPERIMENTAL METHODS**

Two separate TDIC systems were used in this testing. Each system consisted of two CCD cameras and one IR camera. The IR camera in both systems was a FLIR A655sc (16-bit, 640 x 480 pixels, up to 100 Hz). The CCD cameras in the primary TDIC system were Allied Vision Technologies Prosilica GE 4000 CCD cameras (12-bit, 4008 x 2672 pixels, up to 10 Hz). Nikon AF lenses with a focal length of 56 mm were used with an f-stop of 11. The CCD cameras in the secondary TDIC system were Allied Vision Technologies Prosilica GX 1660 CCD cameras (14-bit, 1600 x 1200 pixels, up to 66 Hz). Tokina lenses with a focal length of 100 mm were used with an f-stop of 11.

**TDIC Calibration**

TDIC systems are calibrated using a 2D array of dots with a known separation that are imaged in several orientations. In this study, the CCD cameras were calibrated using traditional dot grids while the IR camera was calibrated using anodized aluminum dot grids developed in this research that rely on emissivity differences to produce measured thermal contrast. All calibration images were processed in the commercial package Vic-3D.5

The CCD cameras were calibrated by simultaneously capturing stereo pair images of the calibration grid at various locations and orientations within the field of view of the cameras. An example stereo pair of calibration images is shown in Figure 1. A set of 20-30 of these stereo pairs was used to generate the individual camera intrinsics and stereo calibration parameters. The intrinsic parameters of the IR camera were calibrated using an anodized aluminium grid with etched dots. A sample image of the anodized aluminium grid viewed from the IR camera is shown in Figure 2c.

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Figure 1. Sample stereo pair of calibration images from the primary TDIC system. (a) Left camera. (b) Right camera.

Mapping of the CCD and IR cameras to the same coordinate system was performed by simultaneously capturing the anodized aluminium grid with all cameras and calculating a rigid body transform between each. Simultaneous capture was enabled in the calibration and testing procedures through a hardware trigger. A sample set of simultaneous capture from each camera from the primary TDIC system of the anodized aluminium grid is shown in Figure 2. This same process was performed independently for each TDIC system.

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Figure 2. Sample simultaneous captured image from each camera in a TDIC system used for rigid body transform. (a) Left CCD camera. (b) Right CCD camera. (c) IR camera.

**Test articles**

Two stitched TDIC systems were implemented to measure the thermostructural response of extruded T-stiffened AA6061 plates. The dimensions of the plate were 0.6 m x 0.75 m x 0.00635 m, with the two stiffeners mirrored about the centerline of the plate with a separation of 0.4 m. The primary TDIC system was used to measure the thermostructural response of the plate. Because the stiffener webs were obscurred from the primary TDIC system by the stiffener flanges, the secondary TDIC system was used to measure the response of the left stiffener web and flange. Test article geometry and measurement surface locations are shown in Figure 3.

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| --- | --- | --- |
|  |  | Primary TDIC System |
|  | Secondary TDIC System |
|  | Both TDIC Systems |
|  | Gripped Surfaces |
|  | Unmeasured Surfaces |

Figure 3. Measurement surfaces on T-stiffened aluminum plate for two TDIC systems.

All surfaces of the sample were painted using Rust-Oleum® Specialty High Heat matte black and white paints for the background and speckles respectively. The background and speckles were applied using an industrial spray gun. The optical thickness for the IR camera, ~11µm, was achieved using the method presented in Cholwea et. al.1 An image from one of the CCD cameras showing the isotropic, non-repeating speckle pattern on the sample is shown in Figure 4.

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Figure 4. Painted surface for TDIC measurements.

**Data Stitching Process**

When visual access to all surfaces cannot be obtained by a single imaging system, full-field results can still be obtained by stitching data from multiple TDIC systems into a single coordinate system. Once each TDIC system has been independently calibrated, a rigid body transformation relationship between the two systems is generated by simultaneously capturing a single speckled measurement surface with both systems. This transformation relationship is subsequently used to spatially synchronize data from the secondary TDIC system to data from the primary TDIC system. Temporal synchronization is achieved by initiating TDIC measurments via a hardwired voltage trigger to both systems. (This trigger is the same used in the initial calibration to sync the FLIR and CCD images.) A sample pair of images showing the surface used for the coordinate transform is shown in Figure 5.

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| (a) | (b) |

Figure 5. Same measurement surface viewed from one CCD camera in each TDIC system. The boxed region was used to create the coordinate system transform. (a) Primary TDIC system. (b) Secondary TDIC system.

**Testing conditions**

The test articles were mechanically loaded with 222kN of compressive force. Once the force was applied, articles were exposed to peak surface heat fluxes of 35 and 40 kW/m2 using radiant heater panels to simulate fire exposure. Testing continued until failure.

**NUMERICAL METHODS**

Finite element (FE) simulations of the experiments were constructed using the commercial software package Abaqus 6.12-EF. The response of the test articles was simulated using sequentially coupled thermal and mechanical analyses. The stiffened plate, heater panel face, and representative grip geometries were modeled in the thermal analysis as seen in Figure 6a. The stiffened plate mesh was seeded at 25 mm in the plane of the plate and a single element was used through the thickness. The heater face meshed was seeded at 51 mm and the representative grip geometry mesh was seeded at 25 mm. All the geometries in the thermal model were meshed using quadratic hexahedral heat transfer elements (DC3D20). A cavity radiation model between the heater and plate was used to calculate the incident radiative heat flux onto the plate. Convection losses from both the exposed and unexposed surface of the plate were calculated using natural convection correlations for a vertical surface by Churchill and Chu.6 A surface temperature of 300°C was used to calculate a convection heat transfer coefficient of 9 W/m2K. The surface emissivity of the plate was taken as a constant 0.95 which is within 5% of values measured by Cholewa et al.1 for temperatures observed in the model. Temperature dependent thermal conductivity and specific heat capacity were used in the thermal model.

Mechanical response was simulated using a nonlinear static analysis. Only the stiffened plate was modeled in the mechanical simulation. Figure 6b contains the meshed geometry used in the mechanical analysis. The plate mesh was seeded at 9.5 mm in the plane of the plate. Two elements were used through the thickness of the plate providing an average element aspect ratio of 3.2. Fully integrated quadratic hexahedral stress-displacement elements (C3D20) were used in the mechanical analysis. Elements in contact with the lower grip region were fixed from translation in all three directions. Elements in contact with the upper grip region were fixed from translation in the horizontal directions and constrained to move equally in the vertical direction to simulate the motion of the upper cross-head. Temperature-dependent mechanical properties including thermal softening, yield strength reductions, thermal expansion, and creep were used in the mechanical models.

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| (a) | (b) |

Figure 6. Representative geometries and grid resolution in numerical modelling for (a) thermal model and (b) mechanical model.

**RESULTS**

Two test articles were tested under the conditions described above. The sample tested with a peak surface heat flux of 35 kW/m2 failed after 11.5 minutes, whereas the sample tested at 40 kW/m2 failed after 8.3 minutes. Each sample collapsed after reaching a peak temperature of approximately 385°C. Full-field measurements of temperature, displacement, and strain on the base plate as well as the stiffener web and flange for two test articles were compared with numerical results. Sample contour plots of temperature near failure are shown in Figure 7. Figure 7a-b shows contour plots of temperature for the primary TDIC system, and the secondary TDIC system, respectively. This shows the limitations of measuring the sample with a single TDIC system, wherein either the plate or the web can be measured but not both simultaneously. Figure 7c contains a contour plot after the stitching process, which shows it is possible to show experimental results in a unified image after stitching. From these unified results, a better understanding of the spatial distributions of measurement variables can be obtained. Additionally, quantitative single point data can be extracted from stitched spatial profiles of either TDIC system and compared with numerical results, shown for the same time step in Figure 7d.

A series of contour plots of temperature overlaid on a deformed test article exposed to a peak heat flux of 35 kW/m2 are shown from various times during testing in Figure 8. Significant failure starts at seconds, as shown in Figure 8f. Looking at the flange of the left stiffener, some observations can be made of the results after stitching. There is a difference in the temperature measurements between the two systems, as can be seen in Figure 8c-d. At point P0 marked in Figure 9, the root mean square difference in the temperature between the systems is of 12-20°C for the duration of testing. In thermography it is ideal to place the camera normal to the surface of interest. For the primary system, this surface was the plate and top of the stiffeners. For the secondary system, it was the web of the stiffener. Thus, the difference on the plate is due to the 2 separate IR cameras imaging the surface from different angles. The root mean square difference of deformation measured between the two systems at P0 is 0.24 mm.

To better compare the numerical and experimental results, measurements at the two line slices shown in Figure 9 were examined for a test article exposed to a peak heat flux of 35 kW/m2. Measurements of deflection and temperature from the experiment for the horizontal centerline, L0, are presented in Figure 10a-b, and the measurements for the vertical line slice, L1, are shown in Figure 10c-d. The gaps in deflection measurements in Figure 10a show sections of the article which were obscured from measurement by the primary TDIC system. By stitching the 2 systems together, the gap in between mm is filled by deflection measurements from the secondary TDIC system. Figures 10b and 10d show the temperature across the sample reached steady state approximately 90 seconds before failure. The maximum temperature across the plate was the same in both centerlines at 385°C. The total range of observed temperatures between the stiffeners for the horizontal slice was 290°C-385°C; whereas the range for the vertical slice was 160°C-383°C. Figures 10a and 10c show the sample began to deflect approximately 120 seconds after the steady state temperature was reached. The stiffeners buckled 660 seconds after the start of testing, as seen by the lines at mm in Figure 10a beginning to rotate and L1 starting to distort in the opposite direction at mm in Figure 10c. The range of observed out of plane deflection in testing was mm.

Similarly, predictions of deflection and temperature from the numerical simulations for L0 and L1 are presented in Figure 11a-b and Figure11c-d respectively. Comparing the results in Figures 10-11, the observed trends of deflection and temperature are similar between the numerical and experimental results. Maximum predicted and observed temperatures at the center of the base plate were 380°C and 385°C, respectively. The temperature predictions were generally lower than observed values for the duration of testing due to idealizations of the heater panels and boundary conditions. As a result, the overall failure time predictions were generally 50% greater than experimental observation.

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Figure 7. Full-field temperature mapped to displaced geometry from (a) primary TDIC system, (b) secondary TDIC system, (c) stitched primary and secondary TDIC systems, and (d) FE simulations.

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| (g) t = 660s | (h) t = 690s |  |

Figure 8. Full-field temperature mapped to displaced geometry for a test article exposed to a peak heat flux of 35 kW/m2 at various times throughout testing.



L1

L0

X

Z

Y

P0

Figure 9. Location of line slices for comparisons shown in Figures 10-11.

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| --- | --- |
|  |  |
| (a) | (b) |
|  |  |
| (c) | (d) |

Figure 10. Experimental measurements of deflection and temperature of a test article exposed to a peak heat flux of 35 kW/m2 at various times throughout testing (a) horizontal centerline deflection (b) horizontal centerline temperature (c) vertical centerline deflection (d) vertical centerline temperature.

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| (a) | (b) |
|  |  |
| (c) | (d) |

Figure 11. Numerical predictions of deflection and temperature of a test article exposed to a peak heat flux of 35 kW/m2 at various times throughout testing (a) horizontal centerline deflection (b) horizontal centerline temperature (c) vertical centerline deflection (d) vertical centerline temperature.

**CONCLUSION**

Full-field measurements of the thermal and displacement response of a stiffened aluminium plate were obtained using a fused thermography digital image correlation (TDIC). Using two systems it was possible to obtain measurements of the web of the stiffener which was obscured from the view of the primary TDIC system. Transforming the measurements of both systems to the same coordinate system, the measurements from both systems were combined into a single resulting data set, which allows for a straightforward extraction of individual points of interest anywhere on the sample. The utility of these full field measurements was shown by examining the temporal trends of deflection and temperature across the horizontal and vertical trend lines. Numerical results were verified by comparing the deflection and temperature at the maximum temperature region from the experimental results.

**ACKNOWLEDGEMENTS**

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