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Experimental validation of high temperature 3D-DIC system for full-field strain measurement of ballooned clad tube

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1. Introduction

According to revised emergency core-cooling-system (ECCS), the safety analysis code system should consider fuel behavior models. During a loss of coolant accident (LOCA) scenario, ballooning and burst of the fuel cladding occur due to internal pressure under a rapid heating state. The large deformation of the fuel cladding influences flow blockage and oxidation at high temperature, and affects results of safety analysis. Several researches have been performed to investigate fuel rod behavior under transient condition. Recently, multi-dimensional fuel codes such as BISON, ALCYONE and DRACCAR have been developed for high fidelity fuel modeling. However, experimental data to validate the multi-dimensional code system still are deficient.

As a non-contact deformation measurement method, digital image correlation (DIC) has been widely applied to various application for the last few decades. To analyze deformation, speckles in the series of specimen images are tracked on the DIC method. For multi-dimensional deformation analysis, stereovision system that employs two or more cameras can be used. The stereovision system can be calibrated using several images of a translated and rotated planar dot pattern with well-known spacing.

In order to further validate performance of established DIC system after calibration, experimental work can be conducted before actual test. Fanxiu Chen et al. (2013) compared 3D profile results of regular cylinder obtained by calipers and proposed 3D-DIC system [1] and Michael Pinto et al. (2014) conducted experimental validation using precision translation stage with custom designed tank before applying 3D-DIC method to actual underwater implosion test [2].

When speckle contrast and quality of acquired images are sufficient, the DIC method can be used to extremely high temperature condition with considering important factors as below. First, high temperature-resistant speckle coating should be used because color or peeling off of the coating can impact the image quality directly. Second, radiation effect from surface of specimen at high temperature must be eliminated when acquiring the image. The radiation can potentially change the contrast of speckles during heating process. Third, effects of heat haze should be mitigated if the measurement is performed in ambient air. Mark and Frank (2011) conducted full-field strain mapping up to 1500℃ with applying alumina and zirconia paints as heat-resistant speckle coating materials, bandpass filter to eliminate the radiation effect, and air knife to minimize thermal turbulence [3]. Xu chen et al. (2012) studied various common heat-resistant coating materials [4] and Wei Wang et al. (2017) performed full-field strain mapping up to 2000℃ using the bandpass filter and blue illumination [5].

In this study, experimental setup of high-temperature 3D-DIC system was established to measure full-field strain of ballooned clad tube. Based on the established 3D-DIC system, validation work was conducted using custom designed translation device.

2. Experimental setup

2.1 FISRBIT with 3D-DIC

An experimental facility named 'FISRBIT' (Facility to Investigate Single Rod Behavior In Transient) has been utilized to simulate ballooning or burst behavior of single rod clad tube [6-7]. To measure 3D full-filed strain, the 3D-DIC system was established with two CMOS cameras, 25 mm lenses, LED lights and commercial DIC software called as MERCURY-RT(Sobriety s.r.o). The two cameras were calibrated using calibration grid with 4 mm spacing. Figure 1 shows the photograph of 'FISRBIT' with the 3D-DIC system.

2.2 Application of 3D-DIC system to high temperature

In order to reduce the possibilities of errors that can occur in the 3D-DIC measurement at high temperature, heat-resistant speckling coating and bandpass filter were employed as below. According to previous results from the 'FISRBIT', range of burst temperature of clad tube was measured from 731℃ to 1065℃ under different internal pressure conditions. Considering this temperature range, white and black paints, which are heat-resistant up to 1093℃, were used to make speckle pattern on the surface of clad tube. As shown in figure 2, the bandpass filter (BP470, MidWest Optical) was employed to reduce interference from red and infrared radiation rays from surface of highly heated clad tube.

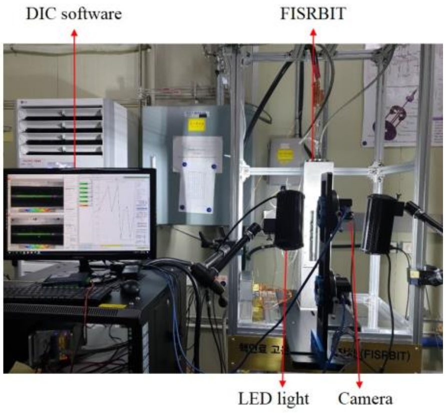

Fig. 1. Photograph of the 'FISRIBT' facility with the 3D-DIC system

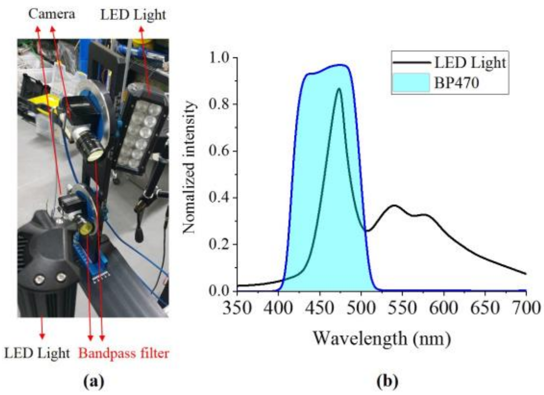

Fig. 2. (a) photograph of bandpass filter mounted on the 3D-DIC system and (b) spectral properties of LED light and BP470 filter.

2.3 Validation device of 3D-DIC system

To further validate performance of the established 3D-DIC system, translation device was fabricated as shown in figure 3. The validation device was installed in 'FISRBIT' hardware instead of 'FISRBIT' enclosure. Plate with speckle pattern can be automatically translated by linear motor. During the translation, moving distance of the plate can be measured from LVDT and the 3D-DIC simultaneously.

The validation work was conducted with two different translation speed such as 2.0 mm/s and 3.4 mm/s. Finally, results of the LVDT and 3D-DIC system were compared.

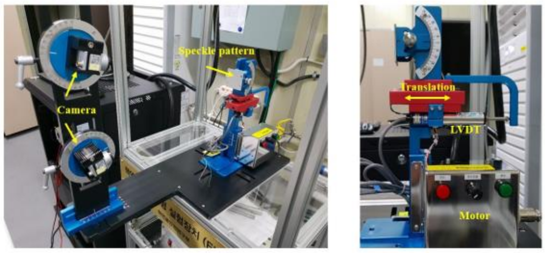

Fig. 3. Custom designed validation device for the 3D-DIC system

3. Results and Discussion

Figure 4 shows experimental validation results obtained from the 3D-DIC system before and after the translation. It can be confirmed that the 3D-DIC calculates all displacements in X, Y, Z direction, and total displacement was calculated as below equation (1).

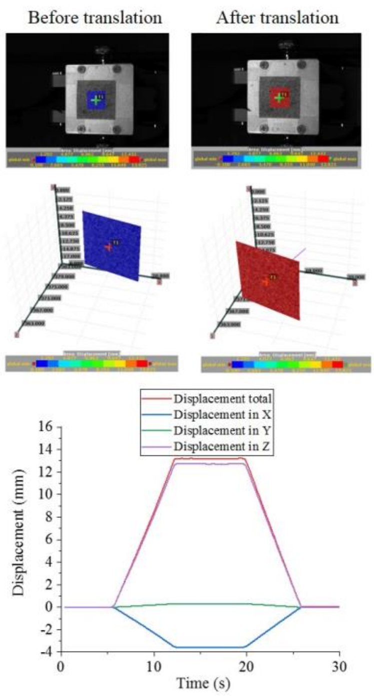

Fig. 4. Experimental validation results from the 3D-DIC system before and after translation.

$$U_{total} = \sqrt{U_x^2 + U_y^2 + U_z^2} \tag{1}$$

The calculated total displacement can be compared with measured displacement from the LVDT considering that the coordinate of the 3D-DIC system is not same with coordinate of the validation device.

Figure 5 shows comparison results of the LVDT and 3D-DIC system with two different translation speed such as 2.0 mm/s and 3.4 mm/s. Table I summarizes relative errors between the results of LVDT and 3D-DIC at some specific time. It can be confirmed that average relative error was below 0.55%. From these results, it can be confirmed that the 3D-DIC system can accurately measure large deformation up to 14 mm. Therefore, the 3D-DIC system can be efficiently applied to the 'FISRBIT' for measurement of multi-dimensional strains when large deformation such as ballooning and burst of clad tube occurs.

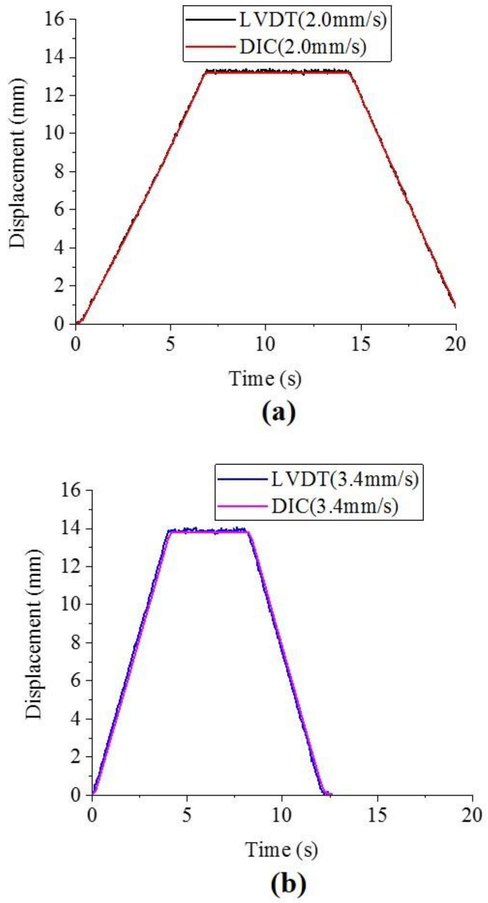

Fig. 5. Comparison results of the LVDT and 3D-DIC system at translation speed of (a) 2.0 mm/s and (b) 3.4 mm/s.

Table I: Relative error between the LVDT and 3D-DIC system at some specific time.

At time (s)	Relative error at 2.0 mm/s (%)	At time (s)	Relative error at 3.4 mm/s (%)
5	0.35	2.5	0.45
10	0.67	7.5	0.70
15	0.42	10.5	0.48

4. Conclusion

In order to produce the multi-dimensional validation date for the multi-dimensional fuel code, experimental setup of the high temperature 3D-DIC system was established. To enhance accuracy of the 3D-DIC system at the high temperature condition, the heat-resistant paints were used for speckle pattern, and bandpass filter was used to reduce radiation effect. The 3D-DIC system was validated using custom designed translation device at different translation speed. As a result, it was confirmed that the 3D-DIC system can accurately measure deformation amount by comparison with the LVDT.

For the future, test matrix of 'FISRBIT' experiment with 3D-DIC will be determined for large deformation of the clad. Cladding temperature, rod internal pressure and multi-dimensional strain will be measured from the experiment. Those data can be used for validation of multi-dimensional fuel code system.

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