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Deformation capturing of concrete structures at elevated temperatures

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Abstract

Reliable deformation measurement is required for proper quantification of fire performance of concrete structures. Predictive capability of models for many critical properties, including Young's moduli, stress-strain relationships and load-induced thermal strains, is first and foremost dependent on such reliable deformation capturing.
This paper first presents a state-of-the-art review of existing methods for capturing deformation of concrete structures at elevated temperatures. Key merits, limitations and challenges associated with each measuring technique are discussed. It is shown that existing testing facilities and measuring instruments generally do not allow reliable direct measurement of deformation and strain of high-temperature concrete. As a result, the deformation has typically been captured either indirectly or outside the heated zones, inevitably introducing additional uncertainty and errors that are difficult to be adequately quantified.
On the basis of that review, the paper details a new test set-up for reliable non-contact full-field deformation capturing of concrete structures at high temperatures using 3D Digital Image Correlation technique. Key features of the new setup that enable to successfully address major challenges of thermal boundary condition, thermal stability of speckle pattern, contrast of image and hot air movement are presented; together with evidences giving confidence to the reliability of such set-up. With its combined advantages of reliable full-field deformation capturing and thermal boundary conditions on test specimens, the new set-up allows to generate required reliable data on performance of concrete at elevated temperatures, thereby facilitating the development of effective rational fire design and analysis of concrete structures.

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Keywords: concrete; elevated temperatures; fire; deformation capturing; constitutive models; DIC.

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1. Introduction

The outbreak of fire in buildings and civil engineering structures can have disastrous consequences, including severe structural damage, significant loss of contents and possible loss of life. Adequate design for fire is thus an essential requirement in the design process, highlighting the critical need for adequate understanding of the performance of structural systems in fire. Such an understanding requires, among other things, reliable realistic measurements of thermal and deformational response of structures at elevated temperatures.

Unfortunately, most existing experimental data have been collected in conventional furnaces or in compartment fire conditions with generally poorly-defined thermal exposure conditions [1, 2] and significant challenges for reliable deformation measurement [3]. The implications of these limitations/challenges on the reliability of collected experimental data, and by extension the analytical/numerical models developed on the basis of such data, are typically more severe for the case of concrete and concrete structures [2, 3]. A research program is thus ongoing at the University of Queensland aiming to generate a more reliable and realistic set of data for improved understanding of concrete behaviour in fire conditions and for developing/validating associated analytical/numerical models, thereby facilitating the further transitioning to performance-based structural fire design of concrete structures.

This paper first presents a brief review of existing methods for capturing deformation of concrete structures at elevated temperatures, highlighting their key limitations and remaining challenges. On that basis, the paper reports details of a new test setup for reliable, non-contact full-field deformation capturing of concrete surfaces at elevated temperatures using 3D Digital Image Correlation technique. Evidence giving confidence to the reliability of the new setup is also presented, together with likely applications of such setup and their potential positive impact on the ongoing transitioning towards performance-based structural fire engineering.

2. Review of deformation capturing of concrete specimens at elevated temperatures

Methods for measuring deformation can be categorised into either contact or non-contact types. A brief review of relevant major measuring methods is given in the following, with a summary in Table 1.

2.1. Contact methods

Contact measurement methods involve the use of such devices as linear position transducer (LPT), linear variable differential transformers (LVDT), compressometers and high-temperature strain gauges that are in direct contact with test specimens to capture the required deformation. Major relevant studies are summarised as follows:

- The LPT (Figure 1a [4]) measures the amount of wire drawn from a spool during deformation measuring. The LVDT (Figure 1b [5]) measures translational displacements through induced voltage changes as the core moves through electromagnetic coils. The use of LPT and LVDT in fire conditions would require thermal protection or materials suitable for exposure to elevated temperatures (e.g., materials which have low thermal expansion, high melting points and no phase transformation up to the target temperature of interest). In addition, the reliability of the deformation measured by these systems was also compromised by the difficult-to-be-quantified displacement of intermediate devices and the machine flexibility [4].

  Using LVDT at the end of a measurement system, Sullivan, et al. [5] reported that reliable measurements could be achieved: The errors of measured thermal expansion of copper specimens were of less than 100 microstrains and the coefficient of thermal expansion was within the range of ±2% of the known value – However, there appeared uncertainties associated with the use of many intermediate devices/connections that had not been properly quantified.
- A compressometer is useful to measure deformation of concrete cylinders up to the peak load level [6-8]. In the post-peak region, with occurrence of extensive cracking, the measurements are typically erratic. Figure 1c showed a compressometer with two rings and three displacement transducers connected to concrete cylinders via thin rods [6]. Another kind of compressometer (Figure 1d) [7] included two Inconel rods which contacted specimen surfaces through cut-out slots on the furnace walls: Again, only pre-peak response could be captured. In addition, the measurement could not be done for all specimens because “the furnace-mounted compressometer was very sensitive to any disturbances such as closing the furnace door, testing machine

vibration, and prolonged exposure to high temperatures” [7]. In another study using compressometer [8] (Figure 1e), the deformation of specimens was only measured up to about 40% of specimens’ compressive capacity at target temperature - The measurement device had to be removed by then to avoid damage to aluminium rods due to the sudden crushing of specimens. In both studies [7, 8], the calibration process to assess the accuracy and reliability of measurement devices at elevated temperatures was not sufficiently detailed. In [6], the compressometer was reported to have been calibrated with an aluminum specimen with well-known thermal and mechanical properties, but details of such calibration were also not provided.

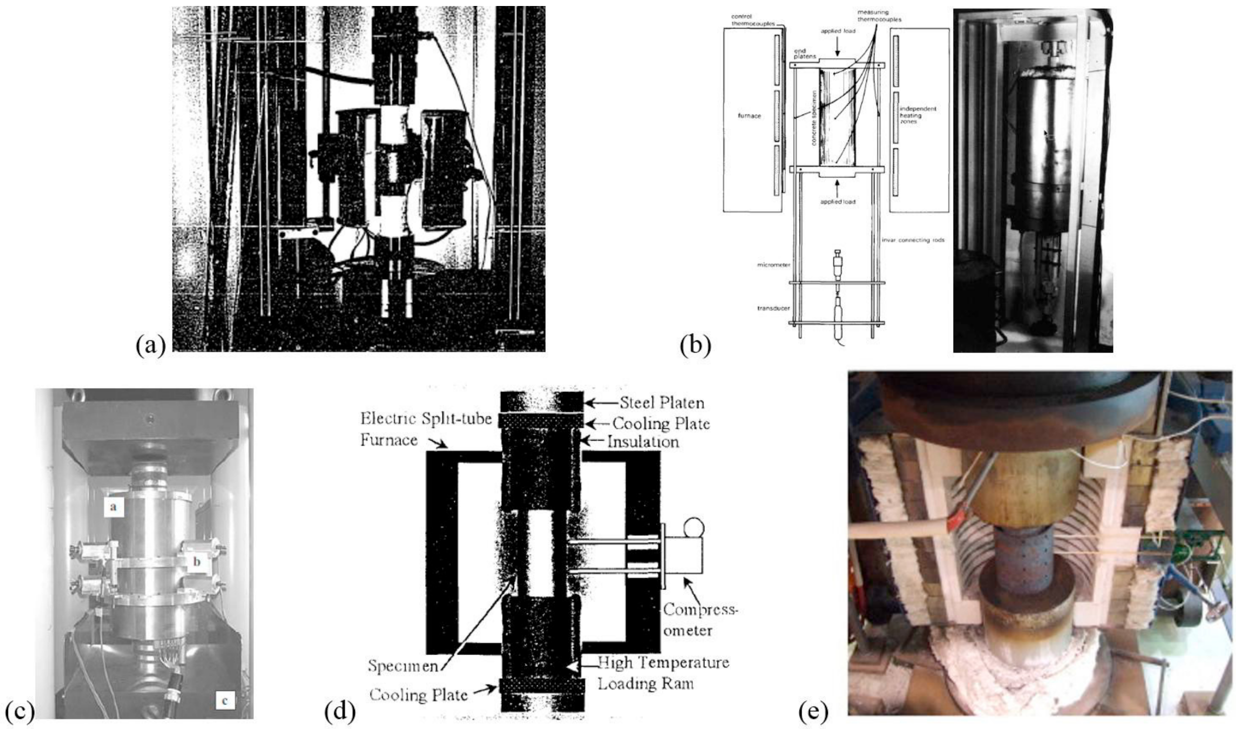


Figure 1. Contact method using LPT (a) [4], LVDT (b) [5], and compressometer (c,d,e) [6-8].

- Strain gauges can be attached directly onto test specimen to measure linear strains at discrete points. Although measurement science for strain gauges is now well understood, there remain significant performance issues in high-temperature applications. High-temperature strain gauges have been shown to be difficult to use and have poorly-understood thermal response [9], and are thus still rarely used in fire testing.
- Fiber-optic sensors measures strains along the fiber length. This is a promising candidate for measuring deformation at elevated temperature [3], but attachment methods between fiber-optic sensor and concrete are currently not well-developed for fire conditions yet.

2.2. Non-contact methods

The two common non-contact methods are laser sensor and Digital Image Correlation (DIC) technique:

- Laser sensors project a laser light spot on the measuring subject and then receive the reflection on a high-sensitivity resolution element [10]. However, current versions of laser sensors perform poorly in fire conditions due to fire spectrum interference at the laser frequency while being often very costly. Due to the above and also to the high risk of damage, the use of laser sensors in fire testing has been rather limited.
- Digital Image Correlation (DIC), a subset of digital image registration techniques, uses cameras to capture images of an object, store them in digital form and then extract full-field shape and deformation [11-13]. DIC

systems process sequential images to compute surface measurements of displacement and strain. Although DIC technique has been successfully used for deformation capturing of surfaces of different materials [9, 11, 12, 14-16], including concrete surface at ambient temperatures, its use for measuring deformation of concrete at elevated temperatures is still in its infancy.

Key challenges for adopting DIC technique at high temperatures includes:

- In a closed configuration (e.g. conventional furnaces [15, 16]): quality of furnace windows, heat haze caused by hot air, thermal stability of speckles and contrast of images.
- In an open configuration (e.g. using laser beam [14], welding gun [17]): heat haze, thermal stability of speckle pattern and contrast of images.

A summary of key challenges associated with major relevant existing measurement methods for concrete deformation at elevated temperatures is given in Table 1. As a result of these challenges, in conventional fire testing, the displacements are typically measured outside the heated zone (e.g. at unheated slab surfaces [18] or at unheated column ends [19, 20]) while strains are generally not measured. Also, in most cases, the displacements are measured at discrete locations selected a priori: Such discrete measurements may miss critical data, thereby compromising the value of expensive and complex experiments in fire and potentially resulting in erroneous conclusions. The field measurement systems that record deformational response data across surfaces would provide a much richer data set for development and validation of analysis models.

It appears from the above review that, the DIC technique, with promising capability of non-contact full-field deformation capturing of concrete structures at high temperatures, is potentially a suitable method for deformation measurement of concrete in fire testing. The question then is how the remaining technical challenges can be adequately addressed to enable such reliable deformation capturing using DIC technique.

Table 1. Challenges associated with existing measurement methods for concrete deformation at elevated temperature.

	Measuring Method	Capacity	Challenges in conditions of elevated temperatures
Contact methods	LPT LVDT Compressometer	Point-wise displacement measurement	Thermal protection or thermally stable sensor is required for exposure to elevated temperatures.
	Strain gauge	Local strain measurement	The workable temperature range for normal strain gauges is limited of only about 100ºC. High-temperature strain gages require further development for increased reliability/applicability.
	Fiber-optic sensor	Multipoint or continuous strain measurement along a fiber	Sensor integrity and bonding methods are not reliable at elevated temperature and need to be improved. Strains transferred from the specimen to the sensor need to be classified and isolated.
Non-contact methods	Laser sensor	Point-wise displacement measurement	Laser beam is interfered and distorted by radiated and reflected light from fires. Further developments in laser frequencies and signal processing techniques are needed for successful application in fire conditions. Setting up laser sensors in furnaces is rather difficult due to limited space and high risk of damage.
	Digital Image Correlation	Full-field displacement measurement	Techniques for improvement in image contrast, thermal stability of speckle, image processing for smoky and air turbulent conditions and quantification of errors and uncertainties need to be developed.

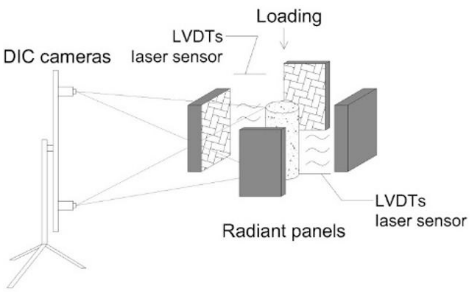
3. A new test setup using DIC technique for deformation capturing of concrete specimens at elevated temperatures

As reliable realistic data on both thermal and deformational behaviour of concrete specimens at elevated temperatures are required to fully understand the performance of concrete structures in fire and also to validate analytical/numerical models of their performance in fire conditions, a new test setup has been developed at the University of Queensland to enable the generation of such data [21, 22]. In addition to the capability of imposing reliable thermal boundary conditions on test specimens, the setup also provides a heating solution without smoke, flame or soot particles, facilitating the application of optical measuring techniques.

In this section, key features of a new setup for full-field non-contact deformation capturing of concrete surface at elevated temperatures is first given, followed by a presentation of evidences that give confidence to the reliability of such system.

3.1. Key features of the new setup for deformation capturing using DIC

The test setup and instrumentation for deformation capturing are shown in Figure 2. The following briefs key features of the test setup that help address the challenges outlined in Section §2 and Table 1.



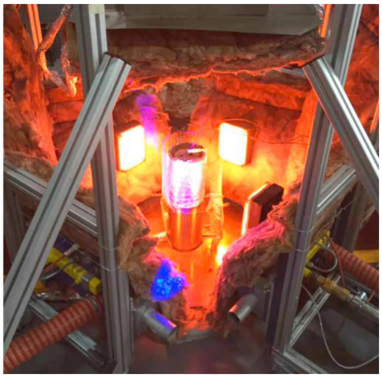


Figure 2. Test setup and instrumentation for deformation capturing.

3.1.1. Speckle patterns

The speckle pattern is computationally designed in accordance with practical considerations for accurate measurements with DIC technique [23]. The speckle size is about 5-10 pixels on captured images and the speckles cover approximately 50% of total pattern area. Silicon ceramic paint VHT Flame Proof, which is workable up to 1000^0C according to the manufacturer, is used to ensure the stability of the pattern within the temperature range of interest.

3.1.2. Band-pass filter and blue illumination for minimising the effect of thermal radiation

At elevated temperatures, the increasing intensity of the light emitted and reflected from specimens' surface and from radiant panels negatively affects the quality of images. As evidenced in Figure 3b, the image becomes saturated if measures are not taken to minimised the effects of such increasing light intensity during heating. Based on the countermeasure proposed by Grant, et al. [24], a Midopt BP470 filter is employed to minimise the effect of thermal radiation, together with a EFFI-Lase-Power-CM-C02-465 blue light to enhance the lighting condition. Such use of band-pass filter and blue illumination has proved to be very effective, as shown in Figure 3c.

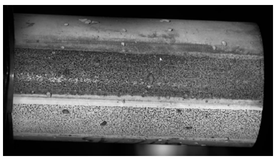
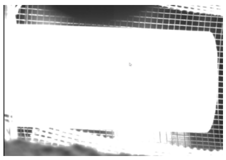
(a)  (b)  (c) 

Figure 3. Captured image: (a) at ambient temperature; (b) at elevated temperature without blue light and bandpass filter; (c) at elevated temperature with blue light and bandpass filter.

3.2. Establishing the reliability of deformation captured by DIC, actuator and strain gauges at ambient temperature

This step aims to assess the reliability of deformation captured by DIC, actuator and strain gauges at ambient temperature. The test setup is as shown in Figure 4. Test specimens were concrete cylinders of ϕ100mmx200mm, each with three 60 mm strain gauges attached on specimen surface (Figure 5). The DIC was set up with two 5 MP cameras and 75 mm lenses. The captured images were then analyzed by VIC 3D 2010 software [25].

Figure 4. The DIC setup and Instron machine.

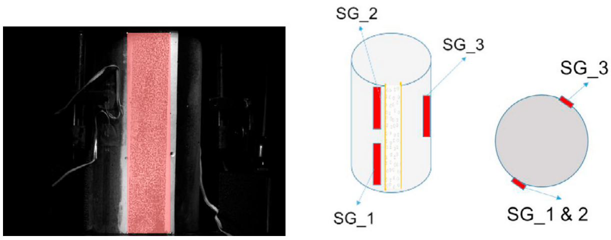
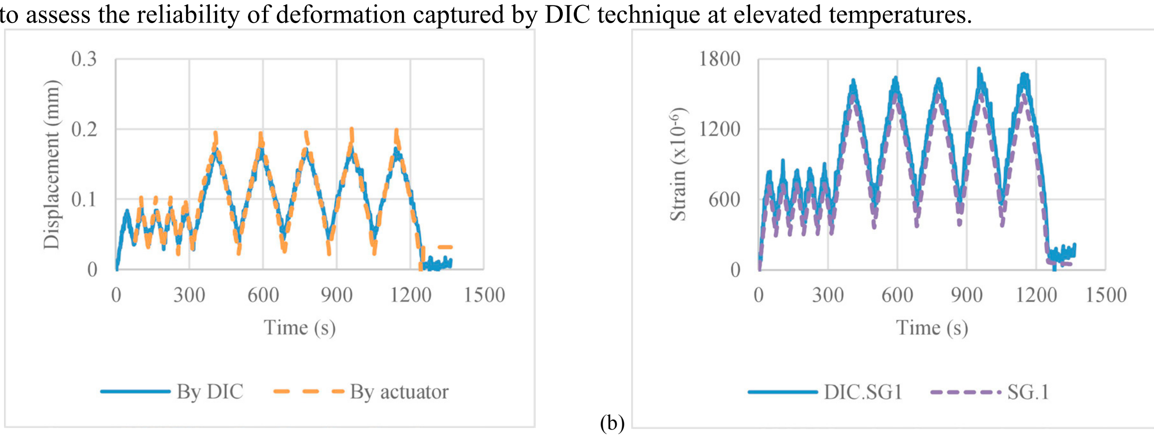


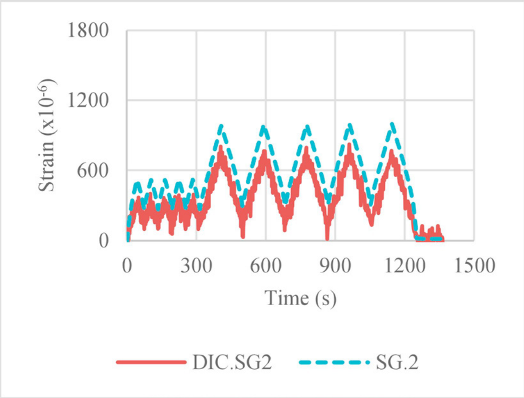
Figure 5. Concrete cylinder with three attached strain gauges.

As can be seen in Figure 6a, there appears a very good agreement between overall displacements of test specimen as captured by DIC technique and by the actuator. DIC-based strains over gauge lengths corresponding to the three attached strain gauges (SG1, SG2 and SG3) were also extracted from DIC-captured data and plotted against those of corresponding strain gauges in Figure 6: A good agreement between the two is also observed.

The good agreement among deformations captured by DIC, actuator and strain gauges at ambient temperature gives confidence to the reliability of all these measuring methods. Also, as the reliability of the actuator is deemed unchanged during testing and thermal loading of test specimens, the deformation captured by the actuator can be used to assess the reliability of deformation captured by DIC technique at elevated temperatures.



(a) (b)



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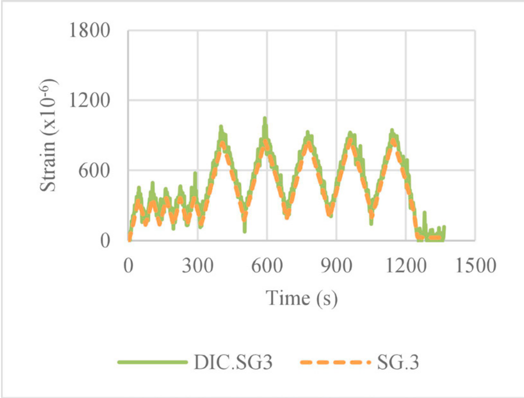
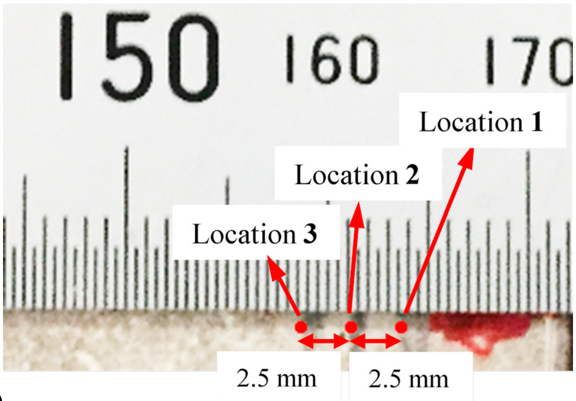


(d)

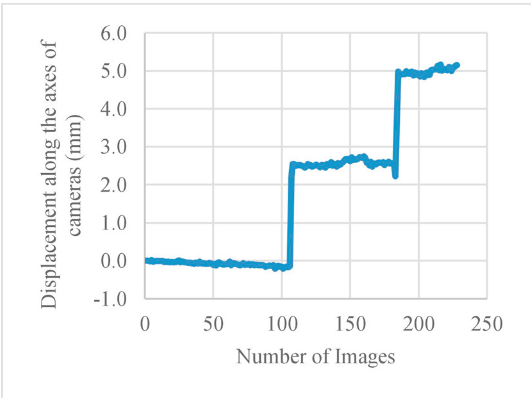
Figure 6. Good agreement between deformation captured by DIC technique and: (a) actuator; (b)(c)(d): three strain gauges

3.3. Establishing the reliability of deformation captured by DIC at elevated temperature using rigid motion test

An effort to test the capacity of DIC at elevated temperature was done by moving a cylinder at elevated temperature. A concrete cylinder was pushed manually by a steel rod along camera axes while being heated. Before each movement, the location of cylinder was marked by pencils around the base. After the process finished, the displacement of cylinder was determined by using rulers to measure distances between marked circles. It can be seen from Figure 7 and Table 2 that the movements as measured by ruler and by DIC technique agree quite well with one another, giving further confidence on the reliability of the adopted DIC technique in capturing deformation at elevated temperatures.



(a)



(b)

Figure 7. Measurement of rigid motions by: (a) ruler; (b) DIC technique.

Table 2. Good agreement between movements as measured by ruler and DIC technique.

Location	1	2	3
Movement as measured by ruler (mm)	0.0	2.5	5.0
Movement as measured by DIC technique (mm)	-0.08	2.55	4.95

3.4. Establishing the reliability of deformation captured by DIC at elevated temperature using compression test

In this part, three concrete cylinders (of ϕ 100mmx200mm) were heated by radiant panels to achieve 150ºC target temperature at the location of 21 mm from the test specimen's curved surface. Test specimens were then compressed to failure under a constant displacement rate of 1 mm/min. The resulting force-displacement curves captured by DIC technique and by actuator are plotted in Figure 8: A good agreement can also be observed, further confirming the reliability of the adopted DIC technique in capturing deformation at elevated temperatures.

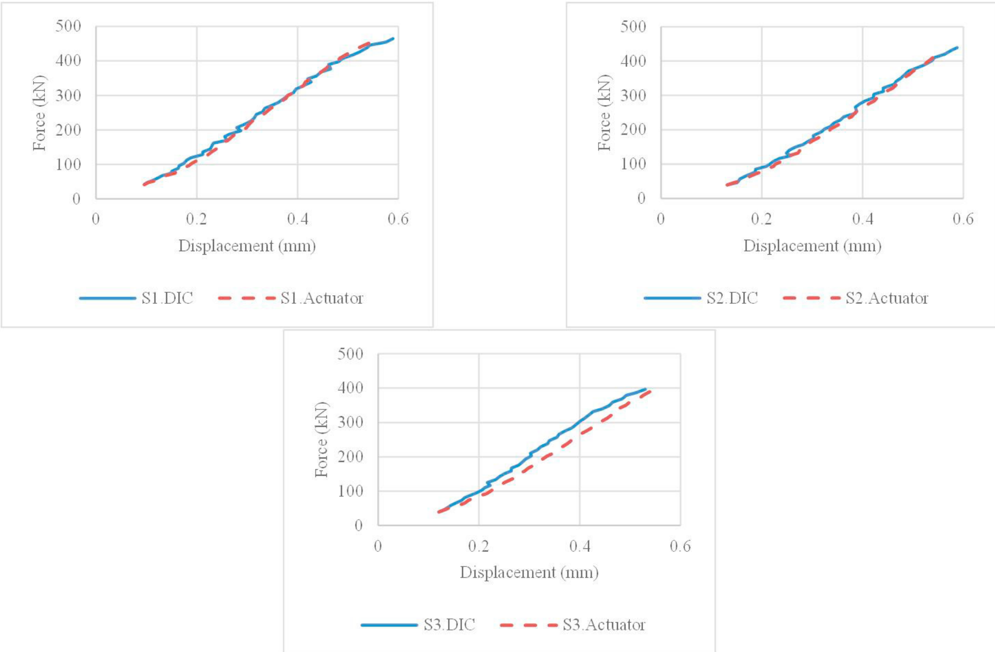


Figure 8. Good agreement between cylinder deformation captured by DIC technique and actuator.

4. Summary and Conclusion

In this paper, a review of major relevant existing methods for measuring deformation of concrete structures at high temperatures is first presented. Key merits, limitations and remaining challenges of each method are briefed, highlighting that existing testing facilities and measuring instruments generally do not allow reliable direct measurement of deformation and strain of high-temperature concrete. Accordingly, the deformation has typically been captured either indirectly or outside the heated zones, unavoidably introducing additional uncertainty and errors that are difficult to be adequately quantified. It is also shown that one of the most promising techniques for deformation measurement at elevated temperatures is that using DIC, a full-field and non-contact solution.

On the basis of that review, details of a new setup using DIC technique for full-field non-contact deformation capturing of concrete surface at elevated temperatures are given, with a focus on key features that help effectively address major challenges discussed in the earlier section. Evidences that give confidence to the reliability of such system are then presented.

Together with reliable thermal boundary conditions on test specimens, reliable full-field deformation capturing would allow to generate required data on mechanical, thermal and deformational response of concrete at elevated temperatures, thereby facilitating the development of effective rational fire design and analysis of concrete structures.

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