OPTICAL CHARACTERIZATION OF HIGH TEMPERATURE DEFORMATION IN NOVEL STRUCTURAL MATERIALS

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ABSTRACT

The traditional fire resistant reinforced concrete assembly is changing. Sustainability and durability objectives are introducing novel structural materials to these assemblies. These novel materials include non-conventional reinforcement (glass fiber reinforced polymers – GFRP, high strength steel – HSS, etc.) and complex concrete mixtures (concrete with recycled aggregates – RA, etc.). Characterizing the high temperature properties of these novel structural components, including their deformation response, becomes essential to explain and model the behavior of contemporary reinforced concrete assemblies under fire exposure. The deformation of structural materials at high temperature can be characterized by uniaxial mechanical testing using a loading actuator equipped with a controllable heating furnace. Contact instruments to measure deformation can be expensive and are easily damaged upon material failure. Practice is to remove this instrumentation prior to material failure, at the expense of valuable data. Recently a non-contact optical measurement technique, also known as digital image correlation, has been proposed for high temperature deformation material testing. The technique herein utilizes a loading actuator onto which a furnace with a specimen viewing window is attached. A hi-resolution camera system measures deformation through the viewing window. Herein, this optical measurement technique is used and assessed in an attempt to characterize the high temperature deformation behavior of three different novel structural materials: concrete with RA, HSS and GFRP. Although RA and HSS could be characterized using this measurement technique, difficulty was encountered with GFRP. GFRP underwent partial degradation through pyrolysis and decomposition of its polymer matrix which affected its surface appearance thereby complicating deformation measurement using optical technology. Critical discussion of the aforementioned optical measurement technique is provided throughout where both advantages and limitations are considered.

INTRODUCTION

Structural designers rely on reinforced concrete for an obvious quoted benefit: 'inherent' fire resistance properties. This claim has had longevity. However, the traditional fire resistant reinforced concrete assembly is changing. Sustainability and durability objectives are introducing novel materials to these assemblies which at high temperature may have very unusual behavior when compared to more traditional material counterparts. When structures are modelled for their behavior and performance in fire, they rely on accurate and conservative deformation models. Traditional materials have been well studied and characterized for their at high temperature behavior over the last century. Naturally, some novel materials have seen limited, if any attention, to their behavior in fire. This reason is not necessarily limited to the fact that these materials are new, but more because measuring and characterizing in fire properties of materials is challenging and not performed with ease.

Traditional instrumentation for high temperature material characterization is difficult to rely on [1]. For example high temperature strain gauges, which can be prohibiting expensive, may be forced to use complicated welding techniques. Their accuracy has also been questioned above 300°C. That temperature is well below what would be expected in a real fire. Further, complicated failure patterns of materials may be localised. For example when uniaxial mechanical testing is performed at high temperature and contact strain measurement is taken in only one longitudinal section of a specimen, the true failure strain (and any associated deformations) may not be rationally quantified. This could mislead an individual to propose failure models which are not representative of the most critical strains and therefore potentially erroneous. Another challenge is the limitation of bonded strain gauges measurement range. At high temperatures, material strain can be of high magnitude, much greater than ambient temperature. Expensive contact instrumentation such as ceramic arm extensometers are typically not feasible for high temperature testing of brittle materials. Brittle materials can fail suddenly and cause damage to the instrumentation. Practice is therefore to remove most contact based instrumentations prior to material failure. This practice can be at the expense of valuable failure data.

Considerable research attention has been made in the last three years towards studying alternative measurement techniques using novel non-contact instrumentations in lieu of traditional contact based methods [2,3]. The authors and their collaborators have focused their research attention on developing novel optical non-contact measurement techniques that can be used at high temperature for the measurement of some emerging and novel construction materials.

This paper, represents an overview of the past and current research progress that the authors and their collaborators have conducted and continue to study, towards developing a suitable and economical non-contact optical measurement technique to measure strain and characterize material behavior at high temperature of innovative materials. The technology is applied to understanding the material innovations being promoted for reinforced concrete assemblies 'at' high temperature – the life critical safety issue. These novel materials include: complicated concrete mixes containing Recycled Concrete Aggregates (RA); High Strength Steel (HSS); and Glass Fibre Reinforced Polymers (GFRP).

MATERIALS

Reinforced concrete, is a traditional construction assembly made of cement, aggregate, water and reinforcing steel. Recently, there has been increasing debate over reinforced concrete's environmental impact, and durability in harsh environments. Industry has therefore responded with many novel material innovations. This section briefly introduces some of the proposed innovations which are considered in this paper.

High Strength Steel

For well over 60 years, HSS has seen significant advancement towards less polluting manufacturing processes using improved furnace and alloying technologies. Today, HSS can be alloyed to have characteristic performance properties *(though at increased cost)*. A typical example of HSS considered herein, is prestressing steel. Prestressing steel can be tensioned to high levels to pre-compress concrete and reduce tensile stresses. In the last ten years various consultancy agencies, aided by advanced optimized design techniques, have studied the sustainability features of concrete structures with tensioned prestressing steel [4]. Thinner slabs in taller buildings have been achieved using this type of steel. These designs have thereby justified decreased concrete material usage enabling green objectives to be met.

Concrete with RA

To address the concerns of concrete's environmental impact, a recent material innovation involves the replacing of conventional aggregates with RA. RA, in the context of this paper, means aggregate that is sourced from crushed demolition concrete waste. These aggregates are graded and substituted for conventional coarse aggregates in a volumetric mix design at varying ratios (0-100%) by mass. RA substitution has shown promising green solution that can meet structural design requirements. This product has decreased reliance on new quarrying, and minimizes infrastructure demolition waste. To date international demonstration projects have effectively utilised this material for construction.

Glass Fibre Reinforced Polymers

In some environments, concrete durability issues can lead to severe corrosion of reinforcing steel.

This can shorten a structure's service life. Polymers do not corrode and therefore such a substitution can be desirable and potentially can extend the service life of this structure by years. This extension in service life eliminates the need of costly and demanding material repairs and the need for entirely new infrastructure so soon into the life of a structure. While not entirely recent innovation, FRP has been developed and studied for years now, the advantage to using GFRP as an alternative to reinforce concrete in critical infrastructures like transportation structures is quite apparent.

METHODOLOGY

In uniaxial mechanical testing of materials, measurement of deformation (strain, cracking deflection etc.) can be made using a non-contact technique known as optical measurement. The optical measurement technique used herein is based on a method commonly utilised by: Queen's University, Canada; University of Edinburgh, UK; and Cambridge University [4]. This technique is an image correlation method. That technique has been used for ambient temperature strain of various civil engineering materials and more recently, through efforts by the authors and collaborators, has been extended for use in at-high temperature conditions. The method relies on taking images through a furnace viewing window. This section details the methodology of the technique. The experimental programme for each material considered herein follows this section.

Camera

The measurement technique used herein relies on a conventional but semi-professional and off-the-shelf Single Lens Reflex (SLR) camera system. The camera is fixed and levelled on a rigid support. The camera then relies on an unobstructed field of view of an object or specimen being considered. For the majority of testing herein a single *Canon 5D* camera with an *EF 24-105mm IS* lens was used. The camera's resolution produces an image of approximately 5760 x 3840 pixels.

The measurement procedure normally begins with taking a reference image of a specimen before any induced external influence is applied (heating, mechanical etc.). In the case of heating, a furnace with a suitable window (one which gives an unobstructed view of a specimen and made of sufficient material to withstand heat), is necessary. After (or during) application of any or a combination of external factors to the specimen, successive images are taken at specified time intervals (usually between 1 and 7 seconds). Images are then sequenced in preferred order. A post-processing software, described below, is used to track deformation of a material from one image to the next in the user defined order.

Post-processing algorithm

An in house developed computational code for post-processing called *GeoPIV8* is used for deformation tracking in this research [5]. The code is primarily maintained and developed by researchers at Queen's University, Canada. The *GeoPIV8* software relies on interpolation functions that analyze image pixel sets. Two successive images are taken of a specimen (one before and one after external influence) and the software processes the movement of a pixel set between the images. Hence the software is a pixel tracking algorithm (Figure 1). At ambient temperature various researchers have been developing best practice guidance for DIC measurement which utilise this software. Researchers have been studying its accuracy with the aim of development for robust measurement accuracy in high temperature materials testing to large-scale structural tests [6,7,8,9].

Tracking paint texture

An adhered randomized and textured paint pattern on materials help the post-processing software to suitably track deformation from one image to the next. The pattern gives a high-contrast image texture which the software can recognize movement easily. At ambient temperature conventional off the shelf paints, while strained, do not decompose or degrade easily, however at high temperature any conventional off the shelf paint can degrade and potentially flame. Therefore it is essential that paints used be suitably temperature resistant to the environment at which they are expected to track deformation. Using conventional room temperature paints at high temperature will result in poor measurement results and possibly a misrepresentation of the combustible nature of a novel material at high temperature. The authors have studied various paints and consulted literature to determine the optimal mixture for application at high temperature. The following paint mix showed suitable robust behavior up to 550˚C [2]. The paints being a *Thurmalox 250* selective black base coat with *Hammerite matte white radiator* paint speckle pattern. Other paints show discrepancies in measuring deformation during their curing temperatures.

Typically a white base coat with black speckled paint can be applied. Though the opposite layering of paint can also be performed. The authors have found applying a black base coat with white speckled paint texture more effective for high temperature testing (Figure 2). The black paint being an available, effective, and more durable primer at high temperature. The white paint used shows faint discoloration at 500˚C. There is temptation at times not to paint a material which appears to have a randomized texture in its natural state. This has advantage as material phase changes can also be considered qualitatively. This implication is considered within this paper.

Measurement error

Optical measurement can have many errors if the user is unaware of the complexity that can be associated to the technique (resolution, camera stability, lens distortions, self-heating of the camera for duration of the test, vibration of the camera due to possible shutter speeds, levelling of camera, focus of image, lighting variations, out of plane movement etc.). There are however simple procedures and appropriate compensations which a user can do to address the aforementioned issues. For example: rigid body analysis can be used to assess the distortion of the camera; a test where images are taken for a fixed duration with no load or any induced effects can help consider vibration, self-heating and lighting effects on measurement; a quick calibration study of images to conventional measurement can determine the associated vibration at various imaging speeds; and levelling technologies can be used assess the alignment of the material and camera to reduce some out of plane measurement error. In many cases the appropriate camera can help minimize error.

Loading frame

All material testing was performed using an *Instron 600LX* servo-hydraulic materials testing frame. The frame was equipped with a furnace and a quartz glass specimen viewing window to allow an unobstructed view of the specimen. Temperature measurements were made using K type thermocouples. Deformation was approximated using the optical measurement technique (Figure 3). Mechanical loading was induced by tension (HSS, and GFRP) or compression (concrete with RA). Test specifics are detailed elsewhere in this paper. The materials testing frame was modified to help extract smoke from the chamber so that the clarity of the images could be preserved. Test procedures are described in the experimental program section for each material considered. Subsequent sections discuss the variations in test procedure for each material. The validation and accuracy of the technique is described elsewhere [2].

Figure 1: Pixel movements between two images taken of a specimen with applied load [2].

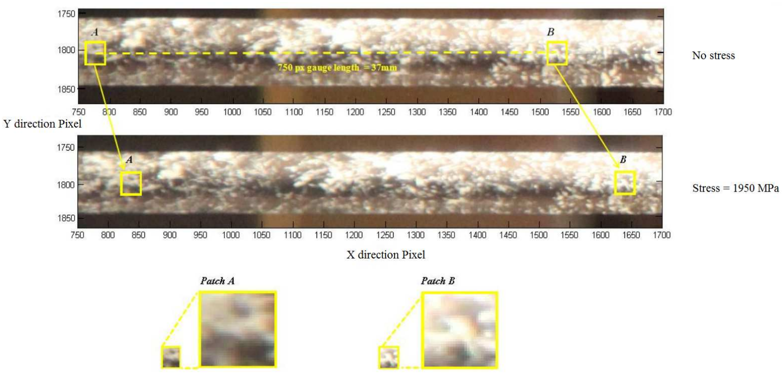
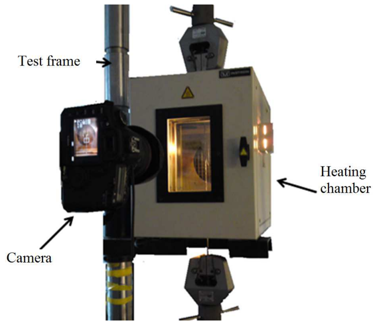


Figure 2: Typical textured paint as applied on concrete.

Figure 3: Loading frame (shown in tension configuration) and camera set up.



HIGH STRENGTH STEEL

Over 70 uniaxial mechanical tests of HSS (prestressing steel) were conducted at high temperature and briefly considered herein. The tests were conducted over 2011 and ended in early 2013 while the lead author was at the University of Edinburgh, United Kingdom. The final results of this test programme are partially published [2,10], with final conclusions currently under evaluation. These tests are considered herein. HSS specimens came from three stocks fabricated in North America, Europe, and Australia-Asia. Each stock was confirmed to be of equivalent grade of 2000 MPa and is denoted herein as BS 5896, AS/NZS 4672 and ASTM A416 respectively. All specimens were approximately 4 mm is diameter.

The initial motivation of this test programme was to validate the aforementioned optical measurement technology for use in high temperature. The validation and verification of the optical measurement technology was satisfactorily conducted and compared to conventional contact instrumentation (high temperature ceramic arm extensometers, and strain gauges) up to 500°C [2]. In addition, this research test programme aimed to provide updated deformation measurement patterns of HSS specimens at high temperature and to increase our understanding of the mechanisms which can cause failure at high temperature. The experimental programme for HSS primarily consisted of: (1) steady state strength tests conducted using a stroke based control of 2 mm/min, after heating to a target temperatures at 2°C/min; and (2) Creep deformation tests. The creep tests considered herein were conducted by heating a specimen to a required target temperature, then rapid loading to a target set point. A selection of transient heating tests (strength and creep) were also conducted but these are beyond the scope of this paper's discussion.

Prior to discussing the deformation characteristics at high temperature of the HSS it is important to describe the analysis procedure. Tertiary or plastic strains that lead to failure will be localised on the material specimen. For example when considering a creep test for steel which exhibits a three phased failure pattern, the tertiary stage will be a manifestation of localised necking [2]. If strain is measured away from this location, the tertiary strains will appear much smaller (they increase towards the location of failure) and therefore the measurement can be an un-conservative representation of the strain which will actually be observed at the localised failure location. The failure phase of creep is important for accurately determining and predicting when HSS may fail in fire. True stress is a parameter which has relevancy for future numerical modelling exercises as well as possible implications for creep modelling and ultimate specimen rupture at failure [2]. Considerable care therefore must be taken when analyzing the images in the post-processing algorithm to approximate the maximum strain and true stress at and near the location of failure. The following procedure was utilised to analyze the test images post-test to approximate these measurements:

1) begin with the last test image;
2) identify the necking location in the last image;
3) the post-processing analysis is run with the test images in reverse chronological order and the dilation of the cross section measured up to the start of the test with the 'future' location of necking then identified – this calculates the true stress; and
4) the post-processing analysis is re-run starting with a longitudinal strain measurement is placed around the 'future' location of necking – this calculates the maximum strain.

Herein this paper remarks on the characteristics observed in high temperature steady state strength and creep tests using the optical measurement technology for HSS. Strength tests were conducted at target temperatures of 100°C intervals. All strength tests beyond 200°C for each HSS specimen indicated a rapid decrease in engineering stress with strain increase after peak engineering stress was observed early into the test. Just prior to failure a characteristic stress 'tail' occurs where strain no longer increases and engineering stress rapidly drops off. When area at the location of necking is measured using optical methods the true stress curve measured is almost linear though does exhibit small increases in stress as the specimen is strained. Once a localised neck clearly emerges the true stress rapidly climbs and is noticeably different than the measured engineering stress. In test repetitions the same observations were observed. This are schematically illustrated in Figure 4 and 5.

The elastic modulus at high temperature for each specimen tested was also considered. Figure 6 illustrates that in all cases measured parameters were higher than those proposed for the original Eurocode giving confidence in the existing parameters for modulus reduction. However these Elastic modulus reductions taken from the steady state strength tests inherently include an amount of plastic deformation damage. Similar observations were observed for strength. Part of the research program considering HSS was to evaluate plastic damage at high temperature and a selection of creep tests were performed to define an accurate creep model. For HSS that is highly tensioned in service, creep is important to calculate the corresponding stress relaxation and possible failure of the steel.

Figure 7 illustrates a selection of three repeat creep tests performed on BS 5896. There is consistent debate that creep tests have a level of randomization, in that their results are not always consistent between one test to the next. The optical equipment has a unique advantage that a strain measurement can be taken almost anywhere on a sample thereby having the capability to measure the maximum and failure strain of a piece of steel. Figure 7 was constructed by considering three creep tests conducted at the same temperature (about 440°C and loaded to a target stress of 647 MPa) while measuring strain across the location of necking using the post-processing analysis procedure as specified above. The creep strain results (after careful removal of elastic strain) are plotted against the well utilised lumped temperature and time coefficient. For simplicity this coefficient is determined through use of the Arrhenius equation. Further details of this calculation can be referred to in Harmathy's research [11]. Figure 7 illustrates that if proper care is considered in test analysis and control, that a creep test could be satisfactorily repeated at steady state conditions.

The most significant outcome of the study using an optical measurement technique for uniaxial mechanical testing of HSS, was that there was significant variability seen between one manufacturer's stock of HSS and those of another despite equivalent behavior at ambient temperature. Figure 4 clearly illustrates the differences in strength at high temperature for two different stocks of steel. Steel production is highly complicated and between manufacturers this can involve the use of completely different fabrication techniques entirely. For example AS/NZS 4672 HSS in equivalent creep tests lasted almost three times longer than its counterparts BS 5896 and ASTM A416, despite showing similar strength behavior at ambient temperatures. The exact reasoning are currently beyond the scope of this paper but worthy of future and continued study as the authors and their collaborators are currently performing.

Figure 4: Steady state strength tests of HSS showing engineering and measured true stress comparison between two different manufacturers at 400˚C.

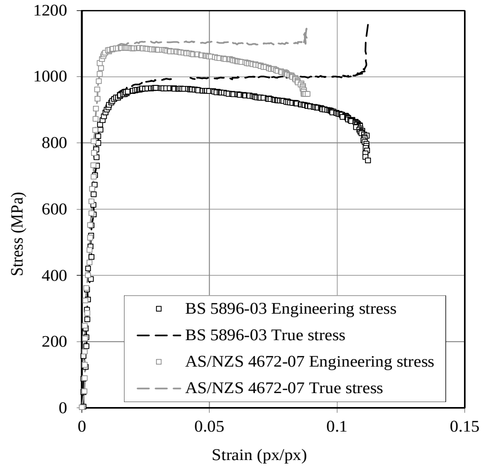


Figure 5: Repeat steady state strength tests of HSS at 300˚C.

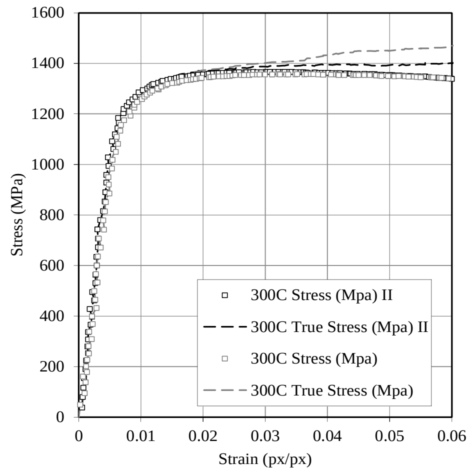


Figure 6: Normalised Modulus of Elasticity for two different HSS in comparison to the accepted Eurocode reductions and proposed reductions.

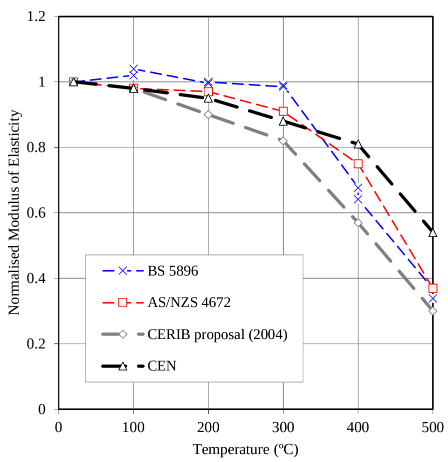
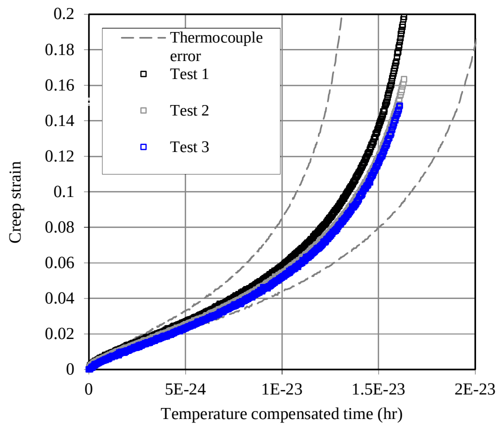


Figure 7: Repeat steady state high temperature creep tests of a HSS.



RECYCLED AGGREGATES IN CONCRETE

Fourteen tests of concrete cubes were conducted at high temperatures. This test series was conducted in late 2013 and has recently finalized. The final report of the test series is currently under evaluation.

Three different mixes of concrete were cast with proportions of 0, 30 and 100% coarse RA by mass. Each concrete mix used a volumetric mix design with a target cube strength of 40 MPa. The mixes used coarse aggregate graded with a maximum size of 10 mm (both coarse RA and conventional). The RA was sourced from a 20 month old de-commissioned lab-scale post tensioned concrete slab of measured 50 MPa cube strength (measured during the time of aggregate sourcing). These tests were originally conducted with the motivation of considering the effect of recycled concrete aggregate substitution for coarse aggregate. The tests were also conducted to investigate limitations of the optical measurement technology; such as the necessity of tracking paint at high temperature and possible test errors.

Because optical measurement techniques necessitate a flat surface to minimize out of plane error, this test series demanded that all samples be cast as cubes rather than cylinders. The size of the furnace window permitted the use of only one camera. It was considered critical that both the transverse and longitudinal strains be adequately measured to investigate possible Poisson effects of concrete at high temperature. The implication of testing cubes rather than cylinders is that the assumption of uniform loading of the specimen is not strictly valid as edge effects from restraint conditions will influence the observed strength behavior and possibly even the Poisson measurement. The difference in strength performance is generally accepted to be about 0.8-0.85 for a conventional concrete cylinder to a cube [12].

Prior to loading, all specimens were heated at a low heating rate of 2°C/min to a target temperature of 500°C. The heating rate was intended to be fast enough so that the tests could still be completed within the safe work schedule of the lab and still ensure mostly uniform heating of the specimen. A sample of concrete in the furnace embedded with a thermocouple at an appropriate depth indicated that such a heating rate would be sufficient to ensure appropriate heating. After heating, all tests were conducted using uniaxial mechanical stroke based control at a constant compression rate of 0.5 mm/min. This type of control was utilised so as to stop testing safely after peak stress of the specimen was observed. Loading was not continued beyond peak stress as there was a risk of debris impact from concrete fracture which could have caused damage to the furnace window. Any damage to the window would have complicated the accuracy of future testing as scratches and pitting could be mistaken by the post-processing software. All tests were loaded on their smooth surfaces and no special preconditioning to the loading surface was done.

There has been considerable discussion in literature as to the Poisson effect in concrete at elevated temperature. Optical measurement technologies enable a unique advantage to assess this. Figure 8 represents a test of 100% RCA at 560°C. At test start there appears no linear proportionality between transverse and longitudinal strain. This is suggestive that concrete is experience transient thermal strains (plastic strains) the moment load is applied at this temperature. However it may also raise interest about the influence from uniformity in loading along the boundaries and its effect on transverse strain measurement. The longitudinal strains near these boundaries however was similar in magnitude to those observed at the centre of the cube. All high temperature concrete tests considered in this study showed this Poisson behavior at high temperature.

Optical measurement was conducted to approximate the thermal expansion of concrete with RCA. Figure 9 illustrates this result and it can be seen that a good linear behavior can be observed during heating of the concrete as could be expected.

Strength and modulus relations indicated that a distinct linear trend in reduction could be observed at elevated temperature. Figure 10 provides two repeat tests for both ambient and at high temperature tests. Even with a complete substitution of conventional aggregates with RA, the sustainable concretes still performed within Eurocode strength reduction guidance, though concrete with RA exhibited less strength retention than its conventional counterpart. Of all tests considered, the optical measurement technique was capable of assessing strain reliably in each test. Before load was applied thermal expansion strain was tracked along the surface of the specimen. Failed concrete typically illustrated higher ductility during elevated temperature tests, while lower ductility at ambient temperature. In all tests, strain at peak stress ranged below 1.5% which was in conformance with expected results as can be seen in the Eurocode.

For one specimen no tracking paint was applied. The intention with this test was two-fold: to assess measurement without tracking paint, and to consider the colour change of concrete during heating [13]. Figure 10 illustrates that without tracking paint on concrete, increased scatter should be expected. Most often concrete is removed post-fire at various temperatures and as an academic exercise there was a capability to consider the at high temperature change. While the pigment in red certainly increased during the test as can be extracted from imaging data, there was no distinct qualitative difference in the images between 20° C and 500°C. After testing and removing of the sample from the furnace the concrete was a hue of pink.

Although optical measurement was done in conjunction with the test, an additional study was performed to assess the temperature of the surrounding area of where the camera was being used and the amount of heat around the loading frame. The concern had been that although cameras are expected to self-heat which can also cause error, the proximity of a camera to the furnace may influence the camera and its lens to expand thereby corrupting the measurement of strain. The authors assessed this by using a thermal imaging camera (a FLIR A302A camera) to consider both the heat the camera had shown during the test as well as the surroundings of the loading frame. The load cell on the frame uses strain gauges to calculate strain and has a maximum operational temperature at 50°C. Therefore it was important to verify that during the test the load cell was indeed within its operational temperature, otherwise the load data could not be trusted. Figure 11 represents a thermal image of the set up with the camera. It was confirmed that these concerns were not an issue for the test configuration employed, however the authors recommend other test set ups be checked for this issue where high temperature tests are conducted.

Figure 8: Transverse and axial strain at high temperature.

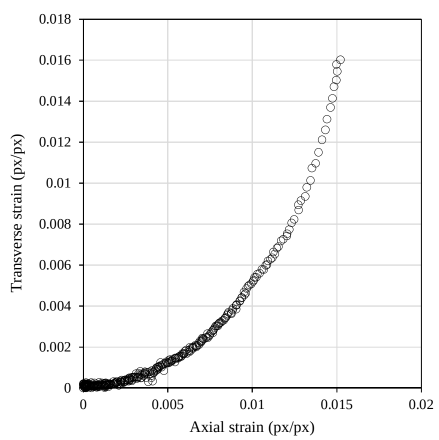


Figure 9: Thermal expansion strain of RA concrete.

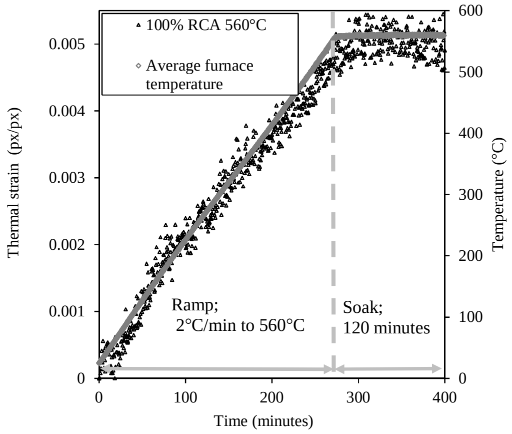


Figure 10: Concrete test repeatability.

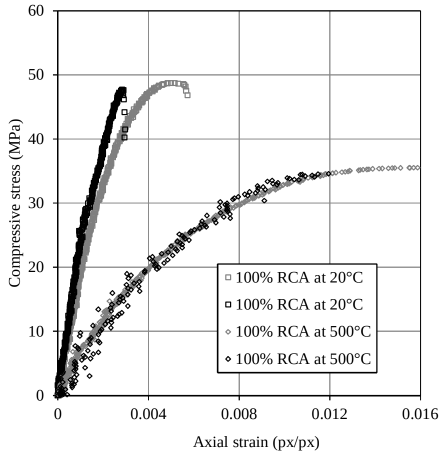
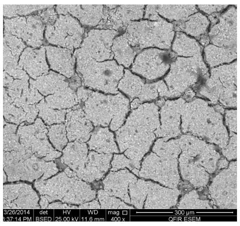


Figure 11: Thermal imaging of equipment frame at load cell showing negligible temperature rise outside furnace.

While most tests were conducted below 500˚C, the authors performed one test near 600˚C (the extremity of both the paint and the furnace) to assess the function of the frame and integrity of the paint on the surface of the specimen. Unfortunately significant effects within the frame from the heating coils of the environmental chamber clearly illustrated that images could show light interference, Figure 12. After heating the concrete coated with the tracking paint to 500˚C and another sample at 600˚C, two respective samples were cut away and assessed using a scanning electron microscope. While the paint showed no observable micro-cracking at 500˚C, at 600˚C there was discrete micro-cracking damage, Figure 13.

Figure 12: Light interference at 600˚C in the heating furnace.

Figure 13: Cracking of tracking paint coating after exceeding its operational temperature limit.



GLASS FIBRE REINFORCED POLYMERS

Four high temperature and loaded tests of a proprietary GFRP are considered herein. These tests were conducted in 2014 and are ongoing at Queen's University Canada. The tests are part of a larger study. Preliminary results of that full study will be published soon [14].

The GFRP used in this test series is characterized as having a polymer matrix and an approximate 80% glass fibre content by mass. The specimen cross sectional area was approximately 198 mm^2. The glass transition temperature of GFRP can be defined as ranging between 90 and 200˚C [15].

The study herein extends the hypothesis that optical measurement could be used without applied tracking paint. The study also considers the use of the optical measurement technology to a polymer based material at high temperature. The rationalization of not applying tracking paint was based solely on the distinct and texturized features of the sand coating found on some GFRPs. There was also concern that unique phase changes could develop with applied heating and these were also of qualitative interest. For these reasons no GFRP considered herein received any tracking paint. Tests were conducted under steady state (heat then load) and transient (load then heat). The tests were performed in duplicate. Observations and measurements were seen to be repeatable. Because GFRPs are composite polymers the four tests herein were intentionally conducted at different phases of polymer degradation in order to study more precisely the behavior and interplay of the matrix and the glass fibres with temperature.

This complexity of the GFRP behavior at high temperature and some associated optical measurement observations can be helped understood by studying one of the steady state tests. In this test the GFRP specimen was heated to about 400˚C at a rate of 5˚C/min under no load. Using the optical technology, this allowed the authors (in the absence of specimen load) to consider the thermal expansion strain, and colour change of the GFRP material. Figure 14 illustrates the thermal expansion behavior of the GFRP as measured by the optical measurement technology. The measured expansion behavior of the bar trends linearly. Un-expectantly, the optical strain measurement does not appear to show any change in performance despite the colour change of the bar (the bar eventually turns from a light to black colour). After reaching 400˚C, the specimen was soaked at this temperature. Approximately 2.5% measured dilation was measured optically. This dilation plateaued in measurement near the end of the soak period. Load was then applied (using a stroke control) at a constant rate to specimen failure. It is conceivable that just prior to application of load, the polymer matrix had completely decomposed leaving the bar to rely on the glass fibres themselves to carry any load [15]. Imaging indicated a cumulative amount of glass fibre breakage which 'discretely' began shortly after application of load. These fractures progressively increased as load increased, eventually altering the surface texture of the bar. Because the fibres seem to be shielded by the sand coating on the outer portion of the bar, attempts to measure strain and approximate the modulus of elasticity with optical measurement were complicated. Figure 15 illustrates the measured stress and strain response of a GFRP sample at 400°C. The outer sand coating constantly exhibited random cracks and peeling as the load was applied. The measured elasticity was much less than what would be expected for the degradation of FRP with glass alone at 400°C. Failure of the GFRP appeared abruptly in the imaging.

A much different interplay mechanism was observed by studying a transient test which had direct consequence on the ability to measure optical strain. Before heating, load was applied. Using the optical measurement technology the ambient temperature elastic modulus was satisfactorily measured at 41.5 GPa. The data used to produce this value exhibited a good R^2 of 0.99 (see Figure 16). Heating then began after reaching a target load level. The load level was maintained for the test duration. Almost instantaneously near the glass transition point, the glass fibres tended to rupture along the outer coating. The sand coating then delaminated and began to 'peel'. This visually started, as confirmed in the images of the test, when the specimen surface temperature was 150°C and continued, at least visually on the surface, until the specimen surface was 230°C. This may be explained as the glass transition phase indicates that the polymer matrix becomes a rubbery state and load may therefore rebalance on the remaining glass fibres. Some fibres may have been loaded more than others possibly contributing to fracturing. The cracking of the sand coating seemed to stabilize after 230°C. This corresponds to a spike in longitudinal strain as measured by optics just prior to when the technology stopped being capable of providing reliable measurement (Figure 17). Beyond 400°C increased cracking was once again seen leading to ultimate failure as had been observed in the case of the steady state tests. Between 230° C and the specimen failure at 426°C no reliable optical measurement of strain was possible. Tracking deformation using optical measurement was pointless beyond the glass transition temperature region in the transient test as the sand coating showed negligible strain increase. Imaging of the test gave similar colour changes as were observed in the steady state tests (Figure 18).

For obvious reason, the authors currently do not attempt to quantify traditional numerical values of true stress or even elastic modulus at high temperature for the GFRP at this stage. Traditional mechanics suggest that the area of the bar would need to be accounted for true stress. To consider true stress on the GFRP, more knowledge of the matrix decomposition would be required to quantify this measurement accurately. Optics like those used for true stress of steel are incapable of deducing the polymer degradation inside the bar. It should be recognized that since GFRPs are typically proprietary in both fabrication and composition, observations seen with these particular bars may not be representative of other manufacturer's stocks. However the results observed herein certainly bring to question added complications with optical measurement on polymers or any other organic material which will experience visual decomposition and significant material surface changes during testing.

Some caution should be emphasised that while this is a limited number of tests a larger test series should naturally be conducted to deduce more meaningful insight to characterize the GFRP material more appropriately. Those efforts are underway by various researchers [14,15]. Additionally the decomposition of the polymer matrix and load shedding to the fibres is currently not well understood and deserves more investigation as observations herein indicate. This can help instil confidence in conducting performance based evaluations of this type of material and structural assembly and also help better direct what we need to measure with optical technology.

Figure 14: Measured thermal strain of GFRP without applied load and tracking paint coating.

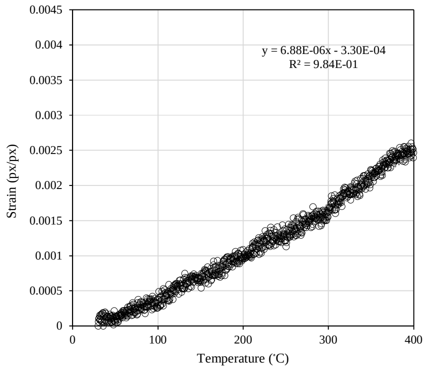


Figure 15: Stress strain of a GFRP without tracking paint coating at 400˚C

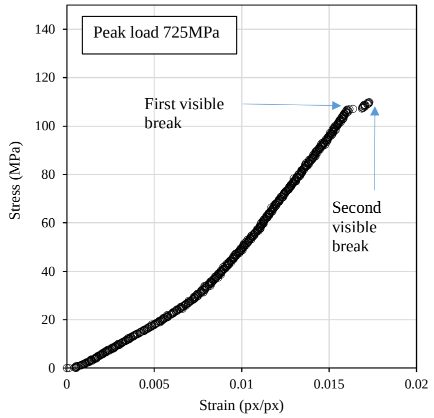


Figure 16: Ambient stress strain of a GFRP without tracking paint coating.

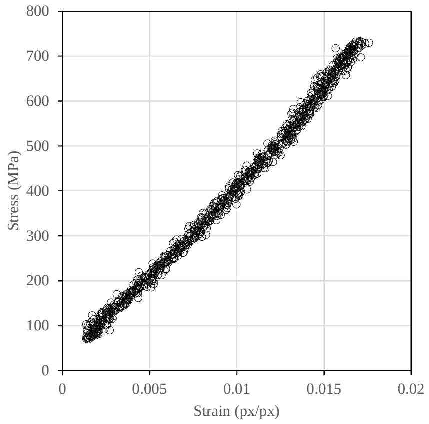


Figure 17: Measured thermal strain and actuator deformation of GFRP with applied load and no tracking paint coating on specimen.

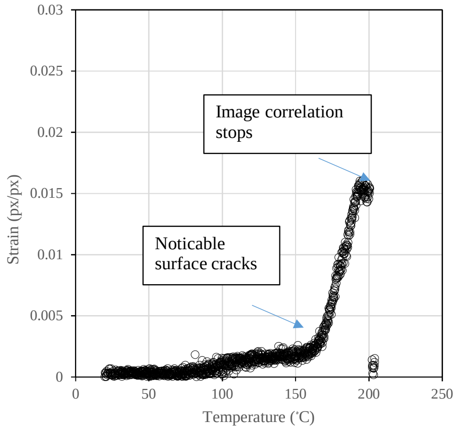
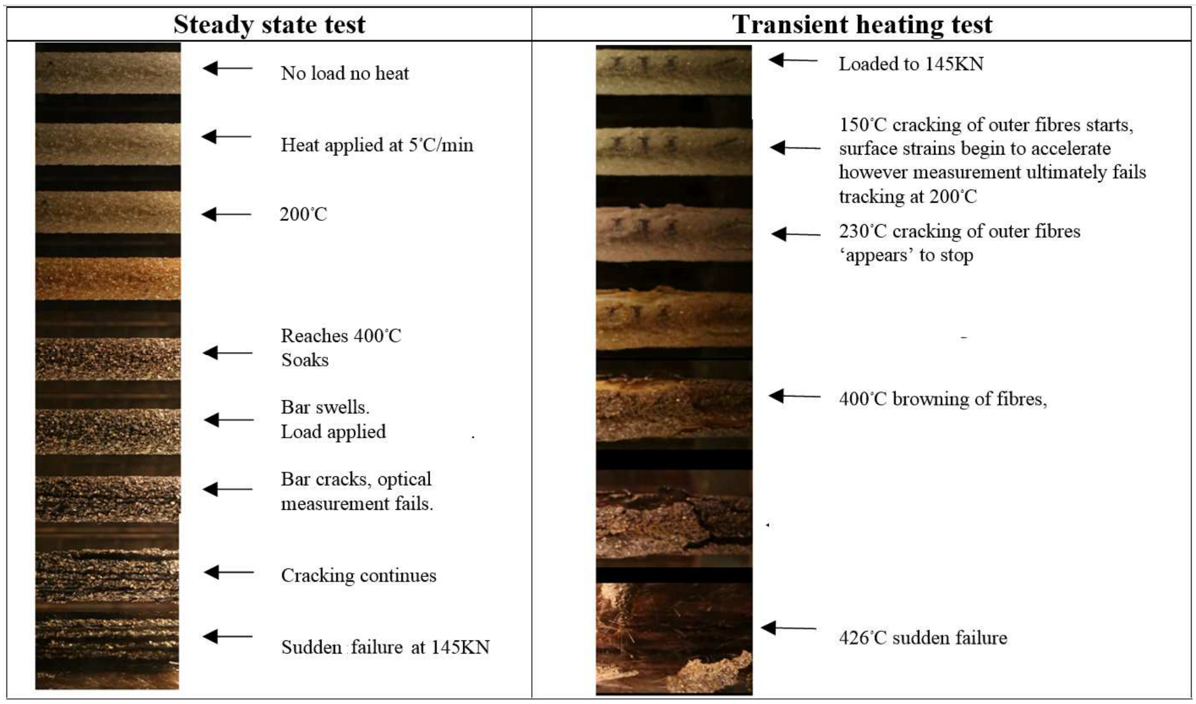


Figure 18: Qualitative visual degradation of GFRP in both a steady and transient uniaxial tensile test with optical measurement failure points presented.



DISCUSSION AND CONCLUSIONS

This paper, represented an overview of the research progress that the authors and their collaborators have conducted and continue to study, towards developing a suitable and economical non-contact optical measurement technique to measure strain and characterize material behavior at high temperature of innovative materials. Herein, an optical measurement technique was used in an attempt to characterize the high temperature deformation behavior and trends of three different novel structural materials: HSS, concrete with RA, and GFRP. Although concrete with RA and HSS could be characterized using this measurement technique satisfactorily, conceptually GFRP could not satisfactorily be characterized. GFRP underwent partial degradation through a decomposition process which affected its surface properties and complicated reliable deformation measurements. As we engineer more alternative materials which can be used in structural assemblies like in reinforced concrete, we will have to consider greater complexities and difficulties with characterizing these material's behavior for fire conditions, especially if we plan to use these materials in a performance based design [9].

While this paper provides additional insight and lessons learned into using this optical measurement technology, it would seem a natural conclusion to attempt to extend the functionality of this measurement technique beyond 500°C in usability. However, the measurement method would need to be evolved (but not limited) to handle smoke (which was easily extracted in these small scale tests, but is more challenging at large-scale), turbulences by heat and material degradations which change the appearance of the material. In reinforced concrete, most constituent materials like those studied herein lose mechanical properties significantly before 500°C is reached. Developing new paint mixtures which extend applicability could have little practicality, unless more extreme heating and analysis is required of the material or a different application of the technology is used. Surface changes will cause the measurement of localized strain and deformation to become highly complex. Changes in colour, shape, texture, will all effect the accuracy of the post-processing algorithm. Based on the observations herein it can be debatable whether the method is to be suitable for materials which pyrolyze like composite polymers or maybe timber. For these materials, the optical measurement technology will have to be used with a level of caution.

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