Using Computer Vision to determine ultimate load for innovative pre-stressed concrete elements using basalt fiber bars

CSHM-7 – Medellín – Colombia
June 22nd-23rd, 2017

Using Computer Vision to determine ultimate load for innovative pre-stressed concrete elements using basalt fibre bars

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Abstract: Structural *Health Monitoring Systems (SHM) can provide valuable information on the structure capacity but the application of such systems is currently limited by access and structure type. This paper investigates the use of computer vision systems for SHM. Computer Vision is a novel method of SHM. It operates by recording motion pictures of a target area on a bridge/civil structure. This paper details the development and validation of a contactless deflection monitoring system in the laboratory using computer vision methods. This system was used to monitor a load test on an innovative floor slab which used basalt fibre reinforcing bars as pre-stressed reinforcement for the precast concrete element. A full scale experimental investigation is carried out at Banagher Precast Concrete Ltd on the precast concrete floor slab. The experiments were aimed at verifying the correct functioning of the pre-stressing system, typically employed for steel tendons, the time-dependant behaviour of the beam during service loading and its resistance, allowing obtaining information about reliability and robustness of this technologic solution. A video image of each test was processed using a modified version of the optical flow tracking algorithm to track displacement. The system provided data on the final failure load which would not have been achievable with traditional monitoring methods as detailed in this paper.*

Keywords: Vison based SHM, basalt reinforcement, field testing

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Introduction

Structural Health monitoring (SHM) senor systems are used to monitor deterioration and provide real information on the capacity of individual structures, hence extending life and improving safety. Changes in stiffness are usually measured using strain sensors, but recent research has indicated that measuring displacement changes from repeated known loading can provide an effective means of determining structural condition [1]. This paper investigates the use of computer vision systems for displacement measurement for SHM and it application for the full scale testing of the structural behaviour of a steel-free pre-stressed slab member.
In the long term, monitoring with cameras is expected to be more broadly utilised for structural engineering purposes because of its potential for inexpensive deployment in real life. While advancing the knowledge by integrating multidisciplinary concepts from theory to application, this research will have direct benefits in areas such as civil infrastructure monitoring which has become a critical societal concern from safety and cost perspectives. The engineering challenge is significant as structural assets across the country reach the end of their intended operational life, placing an enormous degree of responsibility on structural engineers. The structural behaviour of this infrastructure is randomised due to environmental uncertainties. Successful damage detection from existing sensor based SHM systems is limited by determination of optimum sensor locations. Computer vison systems offer a promising alternative by providing a global analysis of the structure which can be used to determine critical changes in terms of crack propagation or material stiffness. The initial development and validation of this system has been carried out through a series of laboratory trials proving this concept of non-contact monitoring. The multidisciplinary field of computer vision is developing rapidly and this research validates its applicability for SHM by replacing traditional sensor systems. Various image processing techniques are assessed and improvements have been made on existing image correlation functions within MATLAB.
The vision based system was subsequently used to monitor the full scale testing of an innovative steel free prestressed concrete section. In recent decades there has been extensive worldwide research to establish a steel free solution for the reinforcement of concrete members, primarily to reduce carbon emissions and address durability issues. Composite materials offer a promising alternative, particularly basalt fibre reinforced polymer (BFRP) bars. Its application to concrete has been investigated [2-4] and field applications have been proven by Taylor et al. [5]). BFRP bars are characterised by a high tensile strength, ranging from 920 to 1650 MPa, and a relatively low Young modulus, ranging from 45 to 59 GPa (Crossett et al. [6]). These particular features make their application in prestressed concrete promising, since their resistance is lower but comparable with that of traditional pre-stressing harmonic steel, while having a Young modulus about four times smaller. This implies that both elastic and long-term prestressing losses occurring in pre-stressed concrete elements due to the shortening of the member will be relevantly reduced with the use of BFRP bars. The use of FRP bars in pre-stressed concrete has been studied by Dolan et al. [7] and Zhou [8] and extended to BFRP bars by Stoll et al. [9] and Crossett et al. [6]. Crossett et al. also studied the BFRP concrete load transfer mechanism with reference to sandblasted bars [10]. A problem for the application of pre-stressing composite bars is the temporary mechanical anchorage prior to the release of the load. All fibre composite materials are characterised by a strong orthotropic mechanical behaviour, which is most performing when the load is applied in the direction of the fibres, while the strength is typically much lower when the load is applied orthogonally with respect to the fibres. The typical anchorage devices used for steel tendons are based on wedges that apply strong lateral pressures to the cables.

Solutions to be applied to fibre composite bars have been proposed by Al-Mayah et al. [11], Carvelli et al. [12] and Schmidt et al. [13] with reference to carbon and glass FRP bars.
This paper details the development and testing of a 10 m long SCC slab member pre-stressed BFRP bars and with GFRP shear resisting trusses. Polyolefin fibres were added to the concrete mix. The design concept and the technical features of the member are presented. The manufacturing of the member is described in detail, highlighting the occurrence of unexpected problems. The experimental results of a 3-point loading test on the member are reported along with the results from our vision based monitoring system. In conclusion comments about the reliability and robustness of BFRP pre-stressed concrete and vison based monitoring methods are provided with reference to both its structural behaviour and its technologic peculiarities.

Background on Computer Vision Algorithms

In recent years camera based monitoring has been introduced to SHM systems, in early applications displacement of several centimetres have been accurately measured by monitoring targets fixed to the bridge [14]. Previous research has highlighted the potential for the integration of imaging devices with traditional SHM technology [15]. Many other SHM applications exist whereby camera based technology is used in conjunction with other sensor types [16-18]. Challenges relating to surface damage of structures have also been addressed using vision based methods [19-21]. Computer vison involves analysing images to determine changing properties of their content. Digital image correlation (DIC) was first proposed by Chu et al. [22] and is now increasing in popularity across science and engineering disciplines. With dramatic improvements in commercially available digital cameras it is becoming a versatile and cost effective analysis method. DIC enables non-contact full field measurements of displacements, hence overcoming the access limitations of existing SHM systems. Other non-contact SHM methods based on microwave interferometry can provide an accurate solution for monitoring structures where access is an issue [23]. There have been significant advances in both SHM and image processing techniques unfortunately these systems are not heavily utilized in practice. The most significant limiting factors are cost and complex system installation requirements. The objective of this research is to develop a low cost non-contact SHM system using commercially available cameras. The data collected is then post-processed to determine structural displacement which will in turn be used as a damage indicator for the structure. A series of laboratory trials have been carried out to develop algorithms for displacement measure prior to field applications.

Algorithm development and testing

The computer vision algorithm developed for usage in this test consisted of 4 steps.

1) Camera Calibration

This step involves obtaining information about the intrinsic and extrinsic parameters of the camera used for testing, in order to accurately convert from pixel units to engineering units. This can range from simply using a reference measurement placed in the field of view of the camera to usage of a camera calibration pattern as developed by [24].

2) Image Registration

This step involves identifying the elements of the images that will be tracked through the video sequence. The possible elements can be colour based, template based or feature based. The algorithm for this test series used the BRISK feature extraction method. A brief summary of the mechanics of several prominent feature based methods is shown in Table 1.

Table 1 Feature Based Methods Description

Algorithm Name	Method
FAST	Combination of point-based and edge-based tracking systems.
Harris- Stephens	Comparison of Intensity Values in the neighbouring pixels.
SIFT	Difference of Gaussian Method to determine potential interest points.
SURF	Second Order Gaussian partial derivations combined with interval images..
FREAK	Cascade of binary strings is computed by efficiently comparing image intensities.
BRISK	Scale-space FAST Based detector in combination with the assembly of a bit-string descriptor from intensity comparisons.

3) Tracking

Once the features to be tracked have been identified, the algorithm uses a Kanade-Lucas_Tomasi(KLT)[25] tracking method to determine the location of the points in subsequent frames. This algorithm works by generating an image pyramid, where each level is down-sampled by a factor of two in width and height. The point tracker begins tracking each point in the lowest resolution level, and continues tracking until all levels have been checked.

4) Displacement Calculation

The final step of the process is to calculate the movement of the points throughout the video by calculating the Euclidean distance between the location of the features in the first frame of the video and in sunsequent frames. This can then be plotted against time and the values displayed as shown in Figure 1.

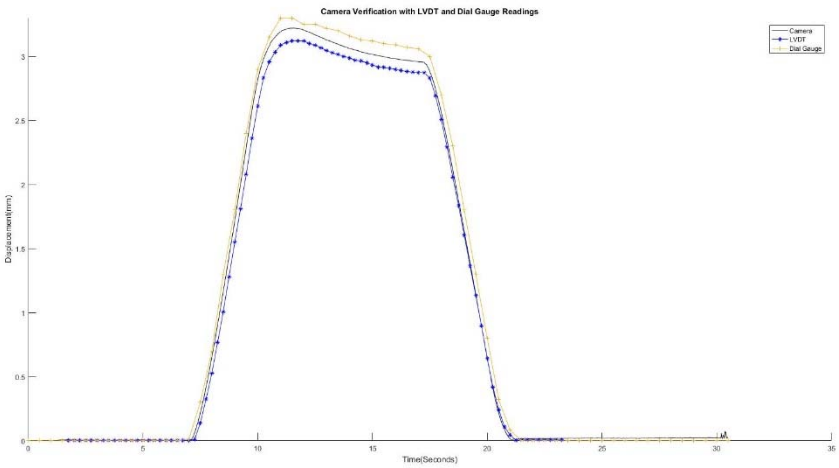

Figure 1 Results from Laboratory testing of Algorithm

Full Scale Experimental Testing of Prestressed Slab

An explicit description of the design of the steel free slab has been provided in [26], a lightened section has been considered as a reference slab cross-section, due to its diffusion in the Great Britain market for flat flooring/roofing. The cross section, shown in Figure 2, is not symmetrical along the vertical axis. The positioning of the pre-stressing BFRP cables is studied in such a way to minimise torsional effects. The member is designed under the assumptions of its use as a roof element, for which the remaining dead loads, waterproofing and thermal insulation layers, may be considered negligible. The C45/55 concrete behaviour curves and mechanical properties provided in [27] have been used. The mean mechanical properties of BFRP bars (tensile resistance fu = 1000 MPa and Young modulus Em,b = 50 GPa) have been considered.

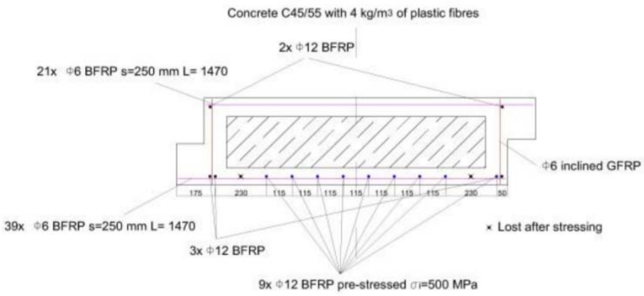

Figure 2: Slab cross section and position of the reinforcement.

The slab member was cast at Banagher Precast Concrete in January 22nd, 2016. Figure 3 provides an illustration of the process, pre-stressing was carried out via an ordinary hydraulic jack with automatic wedge pushing system, as used for steel tendons. The bars have been pulled all from the same side with an initial stress equal to 500 MPa. This corresponds to a load equal to 500*3,14*144/4 = 56,5 kN each, and to an elongation of 15000*500/50000 = 150 mm. The operation has been successfully performed, and the elongation has been checked for each cable, resulting close to the expected value. Tensile failure of 1 bar occurred in correspondence of the wedge approximately 15 minutes after stressing, this initial bar was replaced with an unstressed bar. Two additional failures occurred within the following 30 minutes. The fact that failures occurred after a certain time from the pulling phase indicates a sensitivity of BFRP to loss of strength in time, as typical of timber. As no further failures occurred the casting phase of the element was completed, accepting the loss of two pre-stressing bars and the failed stressing of one. The cast was successfully performed and uniform dispersion of fibres was almost always assured, except for some isolated clots which were removed by hand or with the help of a rake.

Figure 3. Casting and pre-stressing process

Test Setup

The slab member is simply supported on top of concrete blocks placed at the edges. 10 mm thick timber slats have been placed between the member and the supporting blocks to better distribute the load. The load is applied at mid-span by a +300 mm stroke mono-directional hydraulic jack counteracting on a strong steel reaction frame. A steel repartition box beam is placed in between the jack and the slab as shown in Figure 4. Three digital displacement transducers have been placed in correspondence of the mid-span section, one in the centre and two at the edges, A Nikon D810 camera was used to provide a means of determining the slab deflection using the developed vision based method, as shown in Figure 4. Two additional analogic displacement transducers have been placed at about 800 mm from the edges to be able to clear the mid-span deflection from the shortening of the timber slats. A manually controlled hydraulic pump provided with an analogic pressure gauge supplied the pressurised oil to the ram.

Figure 4 Test Rig and Camera Monitoring Location

Experimental Results

The loading protocol is performed by applying load cycles repeated twice at increasing load amplitudes, in order to investigate the crack propagation effect at each load step. A first load amplitude of 25 kN is performed to investigate the pre-cracking behaviour, then the load is taken up to first crack formation. The following load amplitudes are gradually increased up to failure. Based on the section and on the above specified mean material properties, a failure concentrated load of 120 kN is expected. The test results are summarised in Figure 4. The load history (Figure 5a) shows that the beam has attained the expected load, and that it did not fail even at the maximum load reached during the last cycle, equal to 155 kN. The load vs displacement diagram (Figure 5b) shows that first cracking occurred at 70 kN of load, which is a much higher crack load than what expected. The main reason of this over-resistance may be attributed to a large tensile resistance of concrete, benefitting from the fibre contribution. The following cycles show that the initial stiffness is maintained up to 20-25 kN, due to the effect of the pre-stressing force, after which the behaviour softens with a stiffness degradation enlarging depending on the extension of the crack pattern. Since the BFRP bars behave elastically, the residual deflection after even large load cycles is very small.

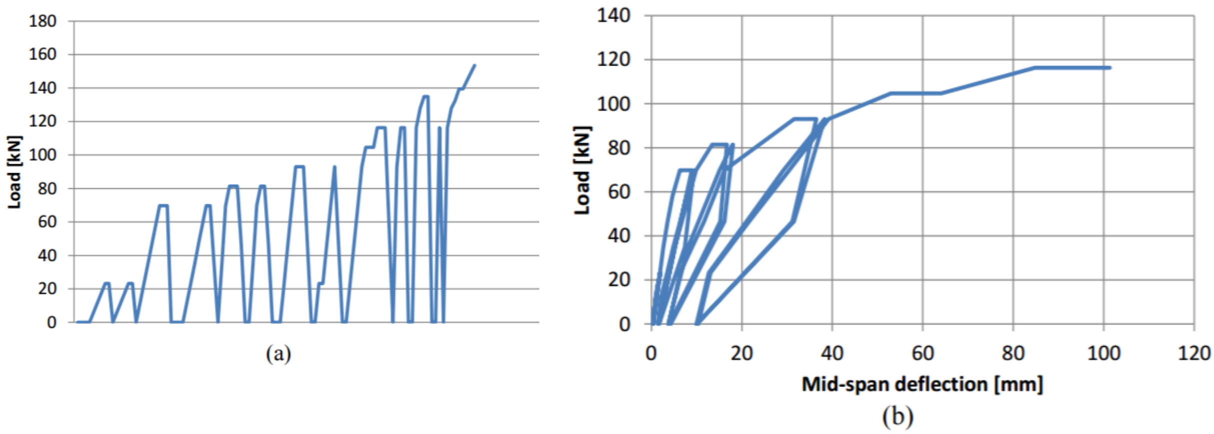

Figure 5 Experimental results: (a) Load history, (b) load vs deflection diagram.

Vision based Results

An area directly above the LVDT was chosen for image registration, and the values were then tracked throughout the series of frames. Figure 6a presents the vision based deflections corresponding to an applied pressure of 20 bars, a factor of 2.33 has been calibrated to convert bars in kN. The graph confirms correlation between the LVDT and vision based measurements. The readings from the camera based monitoring are continuous for the test duration, however the LVDT readings have been taken at discrete times during the test, and the markers indicate the actual readings. The graph shows the LVDT recorded a maximum deflection of 3.044mm compared to a calculated defection of 2.98mm from the vision based method. As the error was less than 2% the vision based method has been validated as a viable method of measuring defection and the results from the other tests confirm this correlation. The vision based system proved critical in the final load cycles since the LVDT's exhausted the available stroke and were removed. Additionally as there was a risk of total failure in the slab section failure which would result in critical damage to the equipment attached to the soffit. However as the deflection measurements were still of significant interest the vision based monitoring was carried out during these tests. This allowed for the measurement of the deflection of the slab under maximum loading and monitoring of the recovery of the section after removal of loading. The results for the final load cycle are presented in Figure 6b.

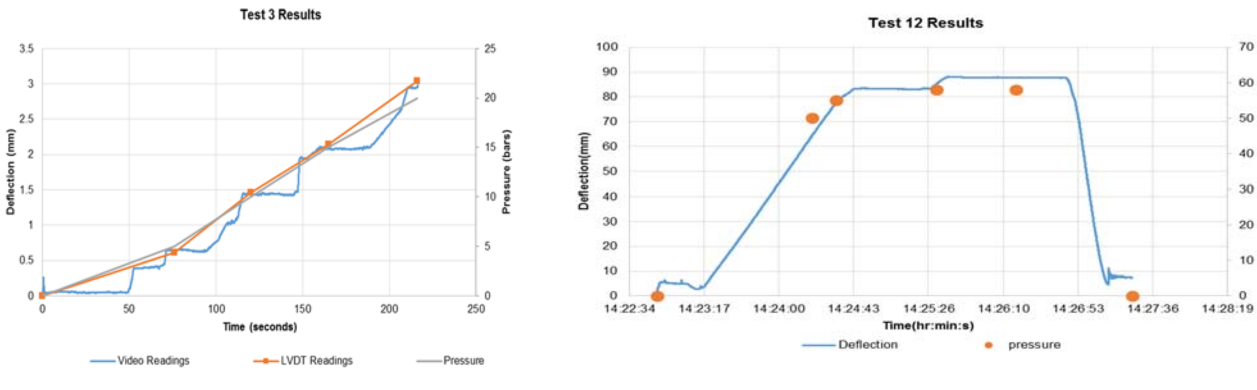

Figure 6a Comparison of LVDT and Vision based deflections for 20 bar load (6b) Vision based deflection for final load cycle

The large deflection of the beam at the +120 kN cycle is noticeable in Figure 7. The crack pattern at the +120 kN cycle is reported in Figure 7. The numbers indicate the pressure level of the pump in bars at the moment of the formation of the crack. A good distribution of cracks allowed to maintain only small crack opening. The formation of the cracks typically occurred with a vertical one with converging inclined cracks at the edges. Polyolefin fibres strongly contributed to the distribution of cracks. The mid-span cracks propagated up to about 50 mm from the beam extrados, inclining towards the concentrated load in the upper branch due to the strong shear action. No explicit shear cracking out from the mid-span area has been observed. After unloading at all load cycle amplitudes, all cracks closed thanks to pre-stressing and the section recovered with a permanent deformation of less than 10mm.

Figure 7 Test beam subject to large deflection and marked crack pattern

Conclusions

The manufacturing of a 10 m long steel-free pre-stressed beam with BFRP longitudinal bars, GFRP shear-resisting bars and fibre reinforced SCC showed an interesting technological outcome: even if the pre-stressing of the BFRP bars has been limited to half of their resistance, the traditional wedging anchorage system used for steel brought to the delayed failure of 25% of the bars due to the concentration of transversal loading in a short distance. The 3-point loading test showed a satisfactory performance of the member, with an efficient elastic performance of the pre-stressing reinforcement even at a load larger than the expected resistance, corresponding to mid-span deflections of more than 1/70 of the span, with small residual deflection and crack closing at unloading. The member could not be taken to failure due to the attainment of an unexpected over-resistance. The crack pattern of the member showed a very good capacity of crack distribution and corresponding low mean crack opening, which is mainly attributable to the polyolefin fibres. The vision based monitoring was found to be a viable method of tracking defection. This method has been validated and provided results in a testing situation which would not have been possible using LVDT’s.

Acknowledgements

The development of the vison based monitoring system has been carried out under the funding of a US-Ireland research program in collaboration with University College Dublin and The University of Central Florida. The full scale experimental activity has been performed within the objectives of the EiroCrete research project, funded by the European Commission within the FP7-PEOPLE-2012-IAPP - Marie Curie Action: "Industry-Academia Partnerships and Pathways". The technicians of Banagher Precast Concrete that contributed to the project are acknowledged.

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