Development and field testing of a vision based displacement system using a low cost wireless action camera.

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Abstract

This paper describes development of a contactless vision-based displacement measurement system for civil infrastructure using a low-cost wireless action camera. Displacement measurements provide a valuable insight into the structural condition and service behaviour of bridges under live loading. Conventional displacement gauges or GPS based systems have limitations in terms of access to the infrastructure and accuracy. The system introduced in this paper provides a low cost durable alternative which is rapidly deployable in the field and does not require direct contact or access to the infrastructure or its vicinity. A commercial action camera was modified to facilitate the use of a telescopic lens and paired with the development of robust displacement identification algorithms based on pattern matching. Performance was evaluated first in a series of controlled laboratory tests and validated against displacement measurements obtained using a fibre optic displacement gauge. The efficiency of the system for field applications was then demonstrated by capturing the validated bridge response of two structures under live loading including the iconic peace bridge. Located in the City of Derry, Northern Ireland, the Peace bridge is a 310m curved self-anchored suspension pedestrian bridge structure. The vision-based results of the field experiment were confirmed against displacements calculated from measured accelerations during a dynamic assessment of the structure under crowd loading. In field applications the developed system was capable of achieving a root mean square error(RMSE) of 0.03 against verified measurements.

1. Introduction and State of the Art

Existing civil infrastructure is under continuous levels of stress from loading and environmental effects whose effects can be detrimental to the integrity of the bridges, so that they must be monitored periodically to avoid dangerous incidents and ensure public safety. Visual inspections remain as the most common method of bridge inspection worldwide [1], is used as a means of detecting obvious damage to structures such as cracks/shifting of components, and is carried out by following a set of established guidelines according to bridge type. However, this approach has many limitations which affect reliability. The method is extremely sensitive to human error, particularly since a visual inspection is rarely carried out by a senior engineer hence it is limited by human capabilities, which means that small displacements and defects may pass unnoticed. A survey of the reliability of visual inspections has detailed the high level of variability in this assessment method [2].

Structural Health Monitoring (SHM) systems provide a valuable alternative to traditional inspections and overcome many of the previous limitations [3–6] and can provide an unbiased and precise means of determining the true state of aging infrastructure. SHM systems allow monitoring of the structural load and response over short periods or for long term, with commonly used sensors including both accelerometers and strain gauges, but there has recently been increased interest in using displacement measurements as a powerful means of assessing bridge condition through performance [7].

Displacement can be measured using traditional sensors, such as the linear variable differential transformer (LVDT), but these instruments require direct contact with the bridge structure to obtain measurements, which can be unfeasible or unsafe in certain scenarios. Accelerometers can also be used for dynamic displacement monitoring up to a point, but they are susceptible to numerical integration error[8]. Global Positioning System (GPS) based sensors can also be used for displacement calculation, but the accuracy of the system is not comparable to that of other systems, with the majority of commercial systems only capable of obtaining accuracy at the centimetre level [9]. Finally, laser vibrometers can provide an accurate measurement along the line of sight at single discrete points [10] but are expensive and cumbersome and do not provide flexibility of measurement available in conventional vision systems.

In recent years, Computer Vision techniques have been applied to the field of SHM, allowing conventional Charge-coupled device (CCD) cameras to be used, as is discussed in [11]. There are two prevalent algorithmic approaches for automatic displacement calculation: Digital Image Correlation (DIC)[12] where a pattern is applied to structures and the totality of this pattern is used as a reference to calculate displacement between frames; and feature-based registration methods [13] where reliable features are extracted from either an applied target pattern or from natural features of the bridge

itself, e.g. rivets, irregularities in the concrete pour etc. These two methods are compared in [14].

Early work in this field is described in [15]. The authors attached two LEDs to a monitoring location on their bridge and used these as targets for their DIC-based system. The low resolution of the camera used in this test along with the necessity of using an attached LED to obtain results make it impractical for use on many types of bridge in service. This method was developed further in [16], where LED targets were used to obtain displacement of a bridge using a template matching system. The high computational cost of using template matching means that such a system is impractical for use in long term bridge monitoring. Further examples of DIC-based methods are described in [17,18]. The main disadvantage is the use of attached targets which limit application to bridge where monitoring locations are acessible. Additional examples of feature based displacement calculation using contact targets are described in [19] [20] and [21].
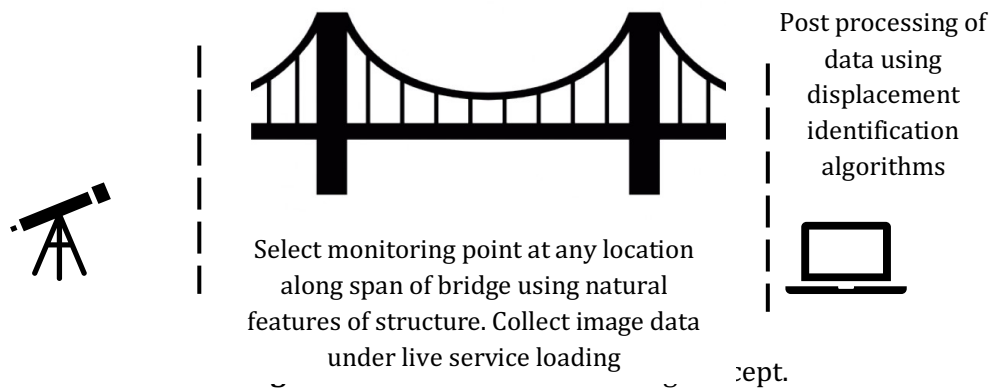
As camera equipment becomes more powerful and affordable, there has been a shift towards feature-based, targetless methods for displacement estimation. This is shown by the work of [22], however the natural feature readings obtained in that paper are not subjected to any ground truth verification by traditional sensor or reference; only a comparison between readings of the camera are used. Further work was carried out in [23] where results comparable to LVDT were obtained at a distance of approximately 30m using professional cameras. These readings are therefore useful for displacement calculation, but the requirement of having a laptop computer connected to the camera used for obtaining video images is not ideal to all locations.

~~This research detailed above has shown that contactless work is viable as a method of displacement calculation.~~ The use of high resolution, durable low-cost action cameras, instead of professional cameras, has been initially explored in [24], but only in a lab trial for a small structure. This paper aims to continue this area of research, demonstrating that low-cost consumer grade cameras can be used effectively, by adding long range zoom capabilities to the action camera to provide greater flexibility in monitoring locations for bridge structures. This paper will also detail the integration of the modified low-cost cameras into an accurate, easy to use computer vision system for SHM which has been validated by laboratory trials and field experiments. The system reported here not only allows taking measurements in places where physical access is physically impossible or challenging, but also reduces mitigates personal risk in the field measurements.

2. System Development

The concept of vision-based displacement measurement is illustrated in Figure 1. In general, a camera is set up on a tripod at a stationary location in view of the bridge structure. The camera is used to record a series of images of a structural region or

Rapid field

element of the bridge under live loading, usually at a minimum frame rate of 25 frames per second (fps). A significant advantage of the system is the ability to measure displacement at any location along the span of the bridge from one stationary camera location.

Post processing of data using displacement identification algorithms

Select monitoring point at any location along span of bridge using natural features of structure. Collect image data under live service loading

2.1. Hardware configuration:

It was decided to use GoPro action cameras [25] for capturing footage in this project as they are low-cost, high resolution (up to 4K), portable and provide wireless functionality for camera control. In addition, these cameras are resistant to adverse environmental conditions such as rain, making them practical for long term deployment in the field. The disadvantage of using GoPros for bridge monitoring is that the standard GoPro lens has a very short focal length, rendering them unsuitable for long distance monitoring of bridge structures. Research was carried out into possible modifications to the camera to add long distance monitoring capability; a solution was found using a modification kit for the GoPro: Ribcage[26](Figure 2). The Ribcage adds functionality for attaching C and F-mount zoom lens to a GoPro; this allows usage of the GoPro as a long-distance monitoring tool.
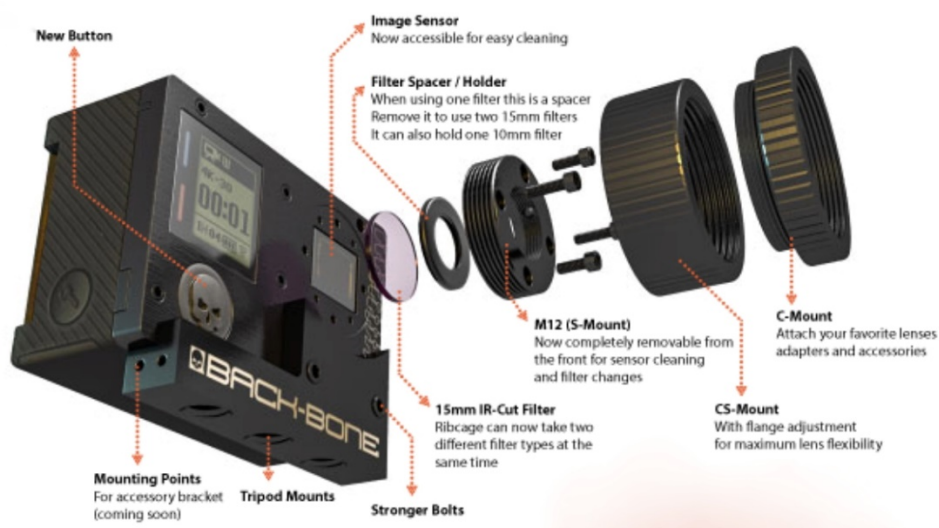
Figure 2 Ribcage Hardware Specification [27]

A low-cost Computar 1/2″ 25-135mm F1.8 C-Mount lens [28] was attached to the GoPro for the testing (Figure 3) detailed in the following sections. The GoPro was controlled during testing using the Capture App[29]for smartphones provided by GoPro, with footage saved to microSd cards for later transfer to PC for post processing, removing the inconvenience and need for wiring between camera and processing devices inherent in other approaches.

Figure 3 Modified GoPro with Zoom lens attached

2.2. Development of Vision Based System:

The development of all vison based SHM systems is dependent on intensive post processing algorithms [30] to convert the captured images into accurate bridge displacements.

A feature-based approach was chosen due to being more robust and reliable than DIC approaches[31] and, when paired with a reliable feature extraction technique, with similar precision. The processing framework is composed of three main blocks, as shown in Figure 4.
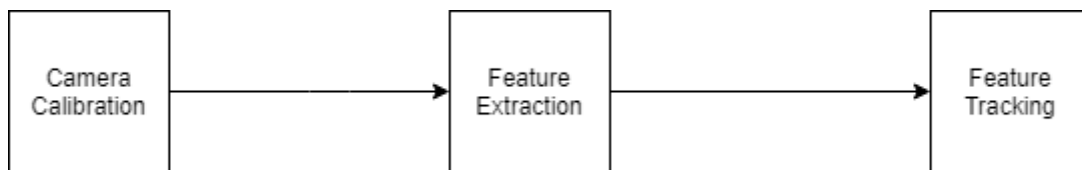

Figure 4 Block Diagram of Algorithm Design

Camera Calibration: Camera Calibration is a method of determining the intrinsic and extrinsic paramenters of the camera used to record the structure motion to remove lens distrortion effects and to provide a scaling factor for the conversion from pixel units to engineering units. The method used in removing lens distortion in this study was [32].

There are a variety of approaches used to determine the scaling factor for converting pixels to physical distance. In [33], a pre-testing calibration method is demonstrated.

$$R = \frac{d}{D} = \frac{f}{p \times Z} \left(\frac{pixel}{mm} \right). \qquad (1)$$

R is the converting ratio, d is a distance on the image, D is a world distance, f is the focal length of the camera, p is the unit length of the camera sensor (mm/pixel) and Z is the distance from the camera to the monitoring location.

The scaling factor can also be determined by use of the formula

$$SF = \frac{D_{Known}}{I_{Known}} \qquad (2)$$

where D_{Known} is the known physical length on the object surface and I_{Known} is the corresponding pixel length on the image plane.

Feature Extraction: This is the process of extracting/detecting salient features from the images of the object to be tracked. Examples of these could be corners, rivets or natural decay in a concrete or steel structure. Processing time can be minimised by only searching for features inside a Region of Interest(ROI). The process selected for use in the algorithm was SURF[34], a robust and computationally inexpensive extension of SIFT[35]. The keypoints provided by SURF are scale and rotation invariant and are detected using a Haar wavelet approximation of the blob detector based on the Hessian determinant. These approximations are used in combination with integral images to encode the distribution of pixel intensity values in the neighborhood of the detected feature. The features detected in our laboratory tests are shown in Figure 5.
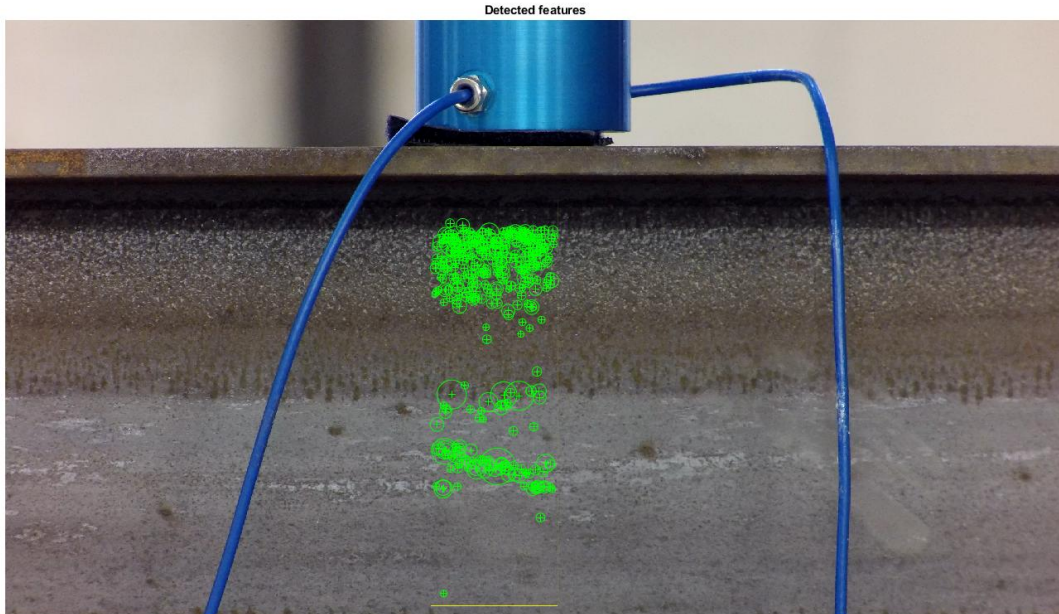

Figure 5 Features Detected in Laboratory Trial

Feature Tracking: Once the points are detected, they must be tracked through subsequent frames to filter outliers and improve the displacement dynamic estimation. Careful

application of threshold values must be maintained during this process, as features may become occluded or vary during the progression of a video. Our system makes use of a Kanade- Lucas Tomasi (KLT) [36] tracker to determine movement of the features detected. This method takes the points detected by the feature extractor and uses them as initialisation values. The system removes outliers using the statistically robust M-estimator SAmple Consensus (MSAC) algorithm[37]which is a variant of the RANSAC algorithm. The MSAC algorithm scores inliers according to the fitness to the model and uses this together with a user- specified reprojection error distance to minimize the usage of outliers in the displacement calculation. Any features that do not meet these thresholds are rejected, with the inliers then tracked on the next video frame using the KLT algorithm. The displacement of the object can be measured in pixels by calculating the relative movement between frames of the centroid of a matrix containing the extracted features. The pixel movement is converted to engineering units using the formula in (2). This continues until all frames of the video have been processed.

This value can then be plotted with respect to another factor: e.g. Load or Time to evaluate the normal or abnormal behaviour of the piece of infrastructure.

3. Experimental validation

3.1. Laboratory Trials

The accuracy of the hardware system and associated post processing techniques were developed and confirmed through a laboratory experimental program. This involved tracking the displacement of a centrally loaded 178mm x 102mm x19mm universal beam with a span of 5.3m simply supported at each end and centrally loaded to induce displacement along the span of the beam. The test configuration is shown in Figure 6; 10 measurement points were identified at even spacing along the span of the beam, Nodes 1-10 (N1-10). A Static load of 332kg was applied to midspan of the beam by means of a loading trolley and crane apparatus. The loading trolley was attached to the beam at midspan and weights were placed inside as shown in

Figure 6. A Fibre optic displacement gauge (FO) with a resolution of 0.03mm was used at various nodes to validate the accuracy of the camera readings. The loading was applied in cycles, whereby an overhead crane would slowly release the basket applying the load to the beam. The applied load was then allowed to settle for at least 10 seconds and was then removed by lifting the basket with the overhead crane. This cycle was repeated 3 times for each FO node location. The camera was set up perpendicular to the beam, at a monitoring distance of 3.2m in all tests and set to record continuously at a frame rate of 25 frames per second (fps). The data acquisition rate of the FO was set to 25Hz to allow accurate comparison of the data. During the loading cycles, N7-9 were monitored by varying the zoom settings on the camera. In each case the FO provided a validated displacement measurement for N7.
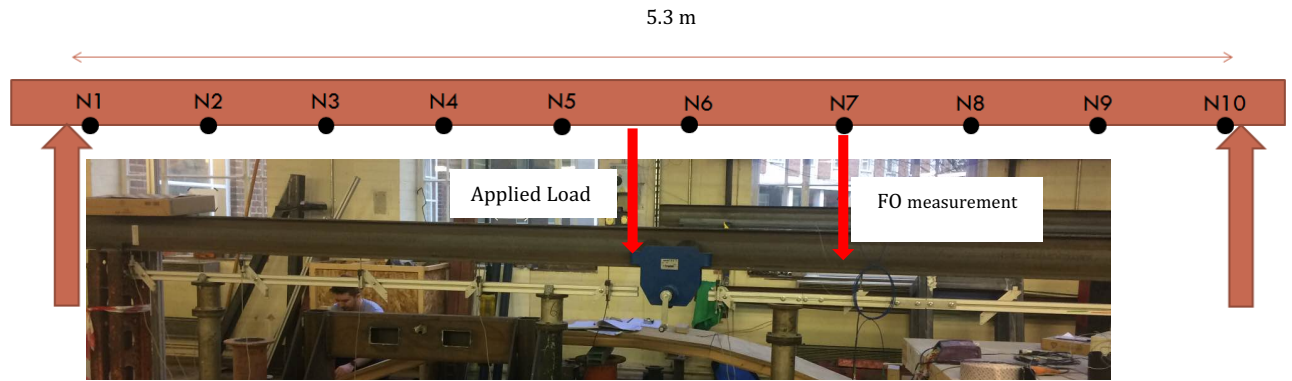
5.3 m

Applied Load

FO measurement

Figure 6 Testing and measurement arrangement

3.1.1 Results

The primary objective of this test plan was to validate the measurements of the camera for displacement monitoring in a controlled environment. As previously mentioned the FO was used as a ground truth for the camera data, the zoom setting on the action camera was varied to ascertain its influence on the accuracy of the calculated displacements, the staged zoom levels are presented in Figure 7. Levels 1-3 correspond to the vision-based monitoring of N7-9, N7-8 and N7 respectively.
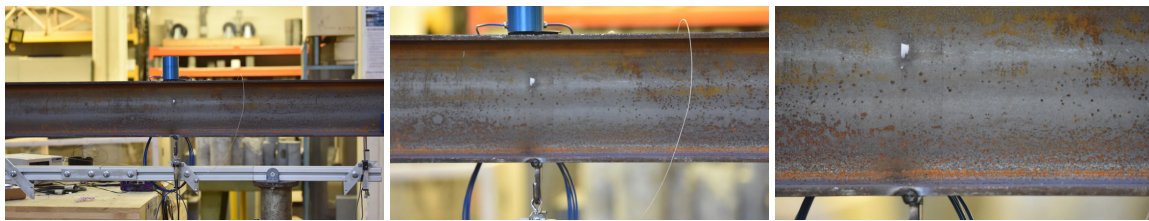
Figure 7 Testing and measurement arrangement

An increase in zoom level would result in an increase in accuracy of the algorithm due to the improvement in spatial resolution; it was desired to determine a threshold for accuracy for the system. The readings taken at each node were converted from pixel to mm using the scaling factor from (2). The results are shown in Table 1.

Table 1 Results from Tests at 3 different zoom levels.

Test	Nodes Monitored	Pixel/mm Conversion Factor	RMSE vs FO at Node 7
1	7, 8 &9	0.7747mm	0.0713
2	7&8	0.4519mm	0.0831
3	7	0.1011mm	0.0434

As can be seen from the table, there is a very small error between the camera system and the FO. **Error! Reference source not found.** show the results from the Test Series. At the highest zoom level, the proposed action camera system is capable of achieving

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accurate displacement of less than 0.1mm at a distance of 3m, and with great accuracy in comparison to reliable but inconvenient FO sensors.
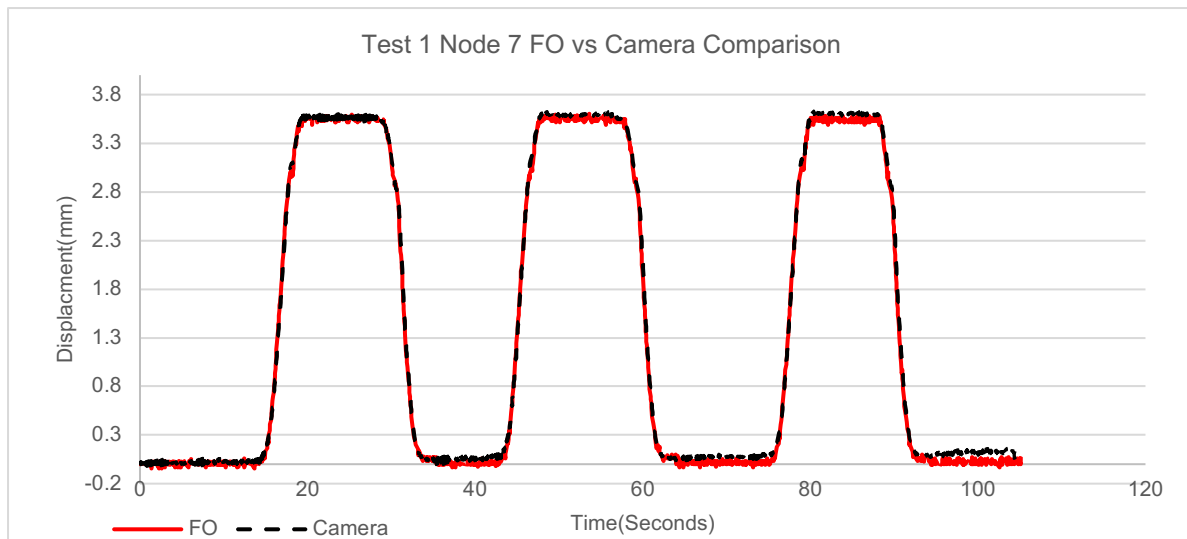

Figure 8 Results from Test 1 vs FO at Node 7
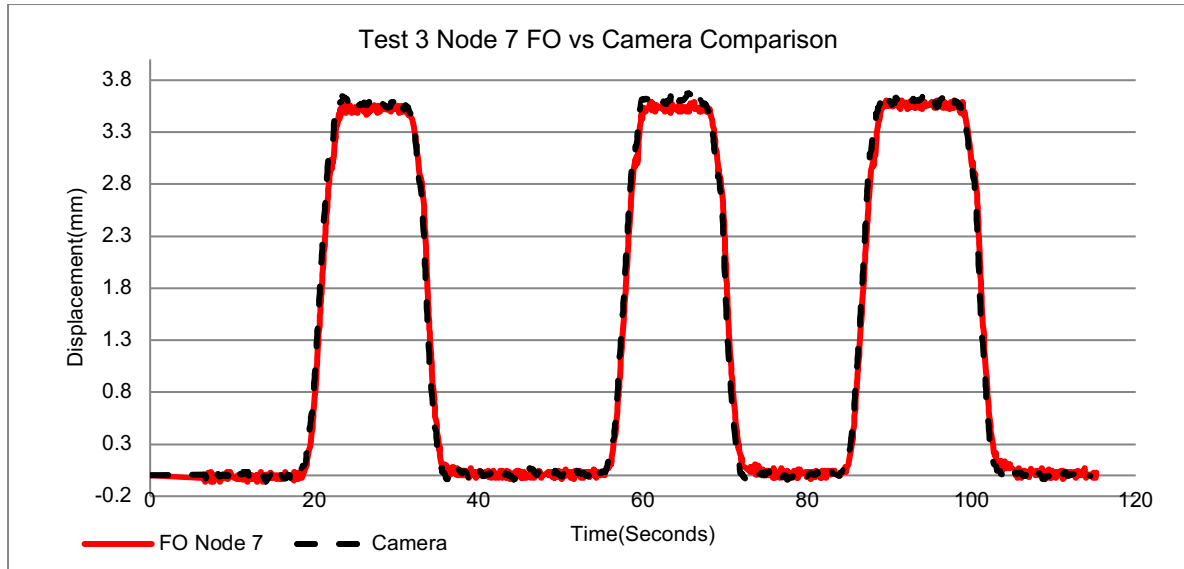

Figure 9 Results from Test 2 vs FO at Node 7

Figure 10 Results from Test 3 vs FO at Node 7

The camera-based monitoring system has been validated at various zoom levels and pixel: mm resolutions vs the FO. This has provided confidence in the usage of the system and proposed post processing algorithms as a means for determining displacement of a bridge structure in the field in a contactless, convenient, safe and low-cost manner.

3.2. Field trial 1: Governors Bridge, Belfast

Constructed in 1973, Governors Bridge is a three-span reinforced concrete beam and slab bridge which crosses the River Lagan to the south of Belfast City. The bridge has an overall length of 62.6m and carries two lanes of west bound traffic from the Annandale embankment to the Stranmillis embankment. The west span of the bridge crosses both the River Lagan and a cycle path, as shown in Figure 11. This span was chosen for monitoring as the soffits of the beams were easily accessible as shown in Figure 12.
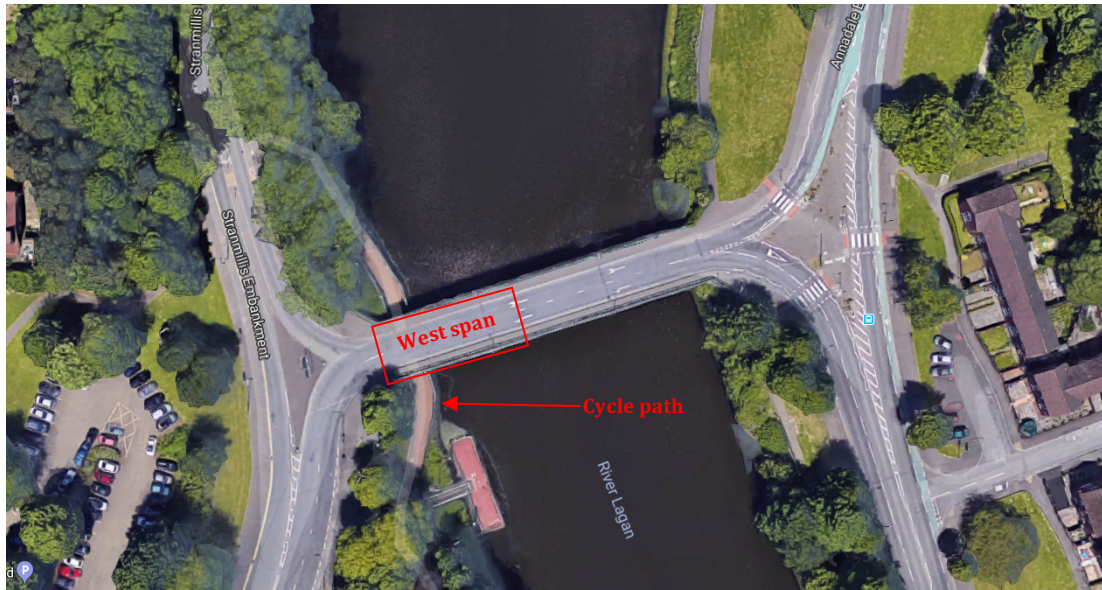
Figure 11: Aerial view of Governors Bridge Belfast

The field test was carried out under normal, non-rush hour, traffic loading on the bridge. Displacement of beam 2 at the location shown in Figure 12 was validated using the FOS system used in the laboratory trials in Section 3.1. Data acquisition of the FOS was carried out using a dynamic interrogator at a scanning rate of 25 Hz. Two action cameras were used in the test, one to monitor displacement from the natural feature of the beam and a second camera to identify the load above the deck, the frame rate for both cameras was set at 25fps to be in sync with the FOS. Action camera 1 (AC1) was located 3.75m from the measurement point, action camera 2 (AC2) was used on the bridge deck to provide information on the vehicle types that caused displacement readings. Pixel: mm conversion was carried out using the formula in (2).

(a)   North elevation
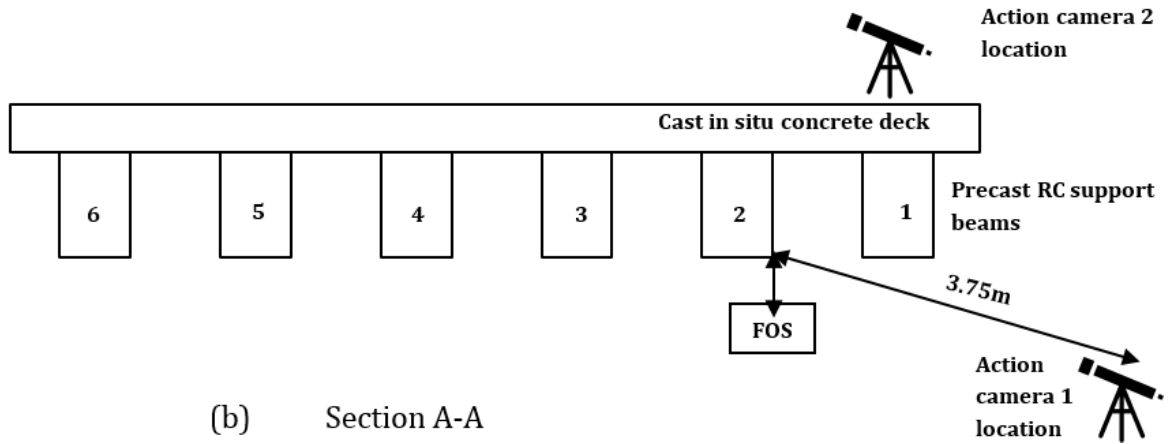
(b)   Section A-A

Figure 12 West Span of Governors bridge showing instrumentation locations.

3.2.1 Results

The displacement response of the bridge under two live loading events is presented in Figure 13 and Figure 14. Beam 2 is located under the south lane meaning that the vehicle position in Figure 13 induced a greater displacement response on the beam compared with Figure 14. The displacement and time histories obtained from the vision sensor and the FOS gauge are shown, together with an image of the vehicle of interest. The identified displacements based on the two systems show excellent agreement, with a RMSE of 0.0314 and 0.0321 for the consecutive loading events, in line with the lab trials estimated error, despite the less controlled environment subject to wind and traffic vibrations. Therefore, it was concluded that the same accuracy in displacement measurement can be obtained from the vision sensor as the current state-of-the-art technology. and the system is suitable for field work.
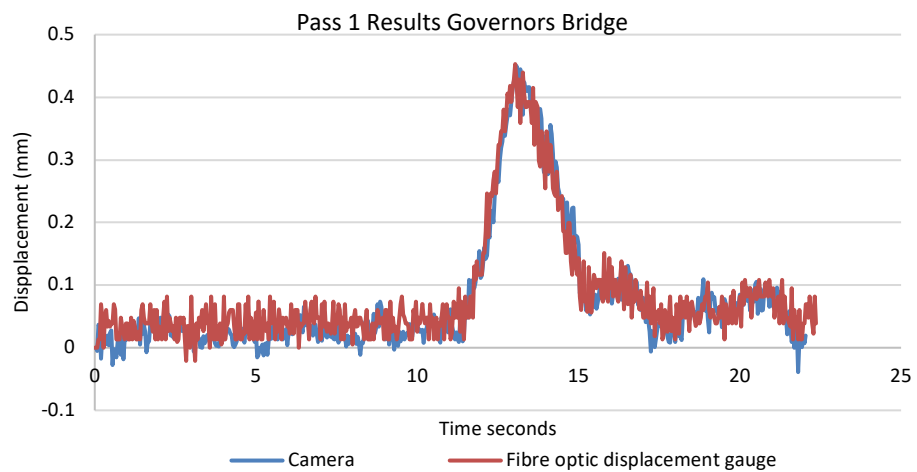
12

Figure 13: Response of bridge under live loading due to 2 axle Class 3 vehicle in south lane
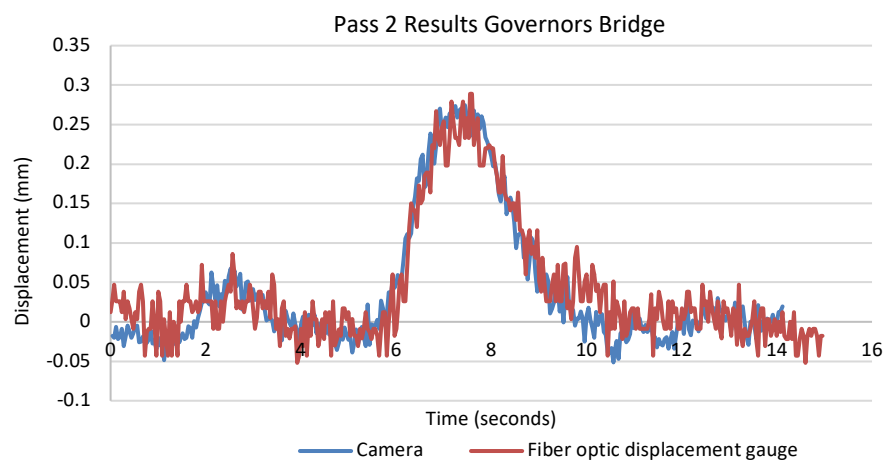

Figure 14: Response of bridge under live loading due to 3 axle Class 5 vehicle in south lane

3.3. Field Trial 2 – Peace Bridge

The Peace Bridge (Figure 15) is a self-anchored suspension bridge with a single 96.3 m suspended central span ('Main Span'), two suspended 63.4 m side spans ('East Span' and 'West Span'), and sections not supported by cables carried by guided supports between the side spans and abutments. At the West end the single section between the support 1 (West abutment) and support 2 is 12.5 m. At the East end sections span 39.4 m from Support 5 to Support 6 and 37.2 m from Support 6 to Support 7 (abutment). The bridge is a continuous steel girder, and longitudinal movement, principally due to thermal expansion, is permitted at the supports and abutments. Pylons are at Support 3 and Support 4, where all degrees of freedom are restrained, although small longitudinal movement of 5 mm is allowed. The details of the design and construction of Peace Bridge, which spans the Foyle River and is a symbol of renewed cooperation between religious communities can be found in the literature[38].
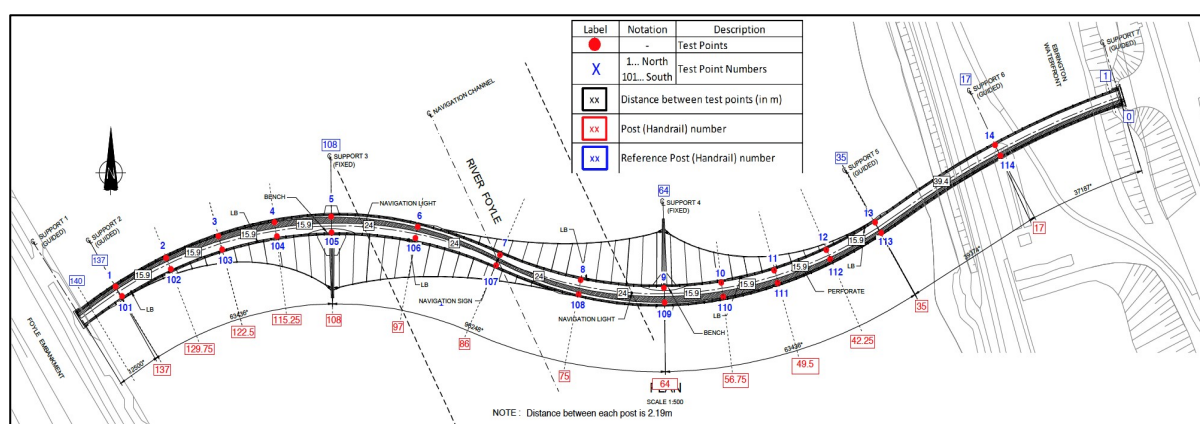

Figure 15: Peace Bridge, plan dimensions and test points for vibration testing (TP's)

In 2016 Full scale Dynamics Ltd (FSDL) in collaboration with Queen's University Belfast (QUB) were commissioned by Transport NI to investigate the dynamic response of the Peace Bridge to crowd loading on the 30th - 31st of October 2016. This SHM research was conducted due to concerns about the vibrations experienced during previous events

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involving significant pedestrian traffic on the bridge. Several separate complaints were made by members of the public stating the structure was subject to excessive movements causing discomfort for users during crowd loading. FSDL and QUB proposed a full dynamic assessment of the structure which would be supplemented with vision-based displacement measurements. The Halloween period was chosen to carry out the assessment as the bridge forms a central element of a large Halloween festival which was voted the World's Best Halloween Festival by TripAdvisor in 2016. The culmination of this festival was a fireworks display, during which the bridge was temporarily closed. On completion of the display, the bridge was reopened to a one-way flow of pedestrians from west to east. The alleged concerning vibrations had been experienced during this event in previous years and it was considered the optimum time to carry out the testing. On Sunday 30th October a sequence of ambient vibration measurements was used to characterise the bridge in terms of modal frequencies, modal damping ratios and mode shapes. Based on these measurements two vibration modes were excited to provide further estimates of their modal frequencies and damping ratios. On Monday 31st October the vibration response of the bridge was monitored before and after the fireworks during which vibrations were recorded at times of large uni-directional pedestrian flow. To determine the viability of the camera-based sensor for future monitoring one location was selected for vision-based monitoring and the results were compared to those obtained by the double integration of the vertical accelerations at the same location.

3.3.1 Measurement equipment and parameters.

Vibrations were measured using a set of Honeywell QA-750[39] accelerometers and recorded using a Signalcalc Mobilyzer ('analyser') [40]. A comprehensive array of signal cables was used to connect 14 accelerometers located at various TPs to the analyser, located in a van parked off the footpath below the bridge between Support 6 and Support 7. Figure 16 shows the accelerometers, cabling and acquisition equipment in use. Accelerations were sampled at 51.2 Hz to provide information in the 0-20 Hz bandwidth

Figure 16: Instrumentation, Function testing QA-740's, van location and analyser.

As shown in Figure 15, the camera was set-up in a tripod on the east bank of the river. TP 112 (Figure 15) was chosen as the location to monitor for vison-based displacements, this represents midspan of the west span. The camera was set up in a matter of minutes compared to several hours required to place and run cables to the accelerometers along the 312 m footway. The accelerometer array also required mains power for the duration

of the testing. The single camera system cannot provide a modal analysis based on simultaneous measurements along the whole length of the bridge. However, if validated it can confirm that the displacements at an individual location are within the allowable limits and be the base for a future multi-camera system for modal analysis. The distance between the camera and the monitoring location was 71.2m and the location corresponds to an accelerometer location to provide a ground truth for verification of the readings gathered by the camera. The distance between two handrail posts on the bridge as shown in Figure 18 was used as a reference for eq. (2) and a pixel: mm conversion factor of 3.457 was calculated. The angle between the camera and the monitoring location was approximately 12°. Experimental work by [23] has shown that monitoring angles of less than 15° do not have a detrimental effect on system performance.

3.3.2 Measurement summary

Figure 15 indicates the full set of 28 test points (TPs) for vibration (acceleration) measurements during the two-day exercise. Mode shapes were assembled from a sequence of measurements on the first day with accelerometers set at different combinations of TPs and directions (V, L, Lo):

- Vertical (V): Positive direction upwards.
- Lateral (L): Perpendicular to bridge main axis at TP, positive direction from South side to North side.
- Longitudinal (Lo): Along the bridge axis, positive direction towards the East side.

On the second day, based on the modal test data, accelerometers were laid out to monitor the bridge response during the heavy pedestrian traffic of the Halloween event. As this paper is focused on the validation of the vision-based displacement monitoring carried out during the crowd loading only this sequence of measurement has been included and is identified as Monit_03 (Figure 15).

3.4. Results
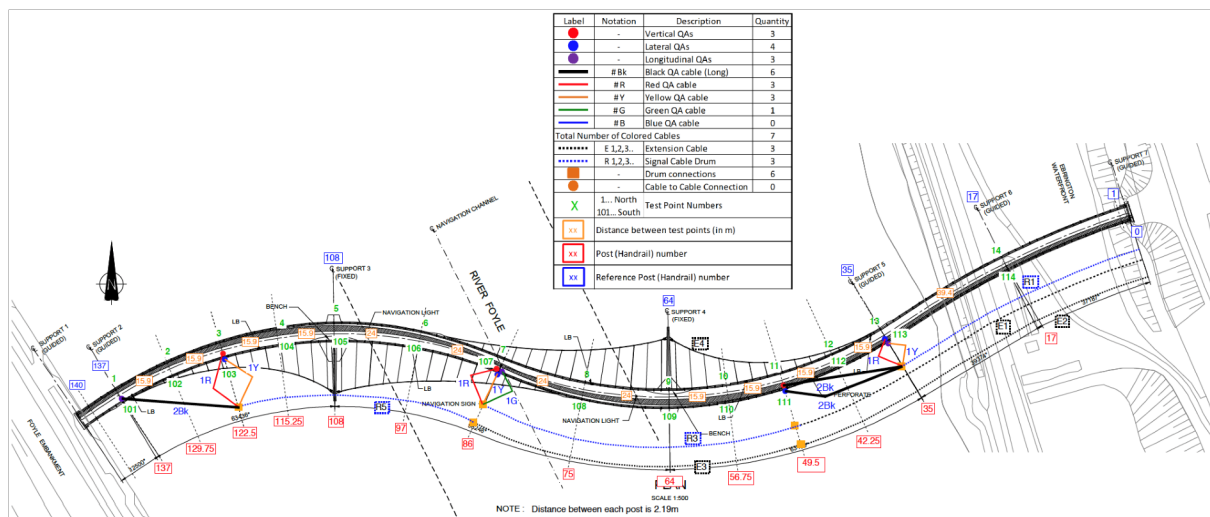
The response of bridge immediately after the fireworks display was chosen as a suitable monitoring period to compare the results, as it closely replicated previous incidents in which excessive movements had been reported. The bridge was opened to one-way flow of pedestrians from West to East. This happened twice because congestion at the East exit resulted in an accumulation of a large stationary crowd at the first bridge was opening. Pedestrian flow was halted to let this crowd dissipate after which the bridge was reopened, and a large West-East crowd movement developed again. When the West to East flow had started to subside, pedestrians could move from East to West, but the dominant flow remained West-East. The displacements obtained from the double integration of the acceleration signals at location 111V and the camera sensor at the same location are presented in Figure 18. The monitoring location is circled in red, and as monitoring was carried out in reduced lighting, a corresponding daylight image has been added for clarity. Camera vibration caused by environmental conditions was removed through image stabilisation [41]using the stationary building in the background of the image as a reference point. Again, the displacement measurements achieved from the camera sensor show good correlation with those obtained from the accelerometer. It is clear from the plot that the results are not as accurate in this case. However, given the poor lighting conditions, measurement distance (resulting in a minimum displacement resolution of ~3.5mm) and the plausible own error during integration of the accelerations, the findings are certainly promising for this low cost monitoring system.
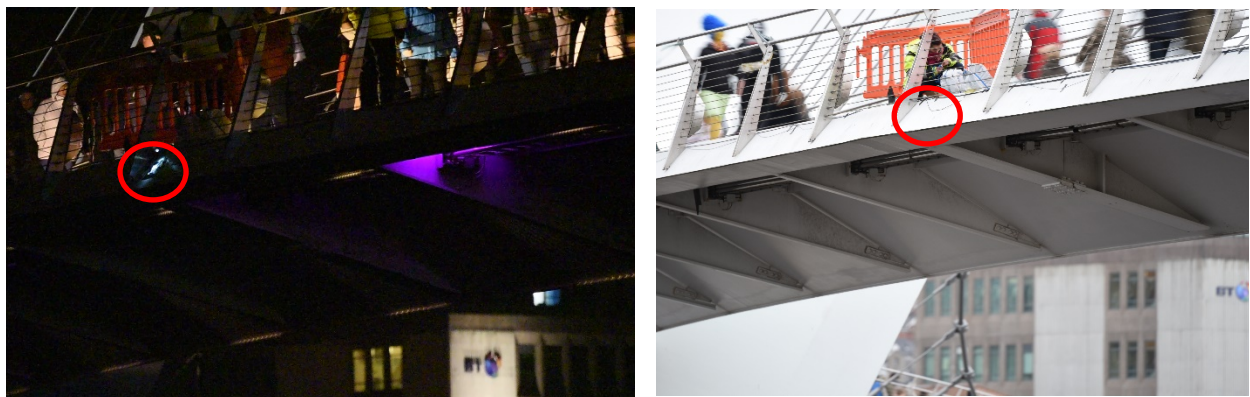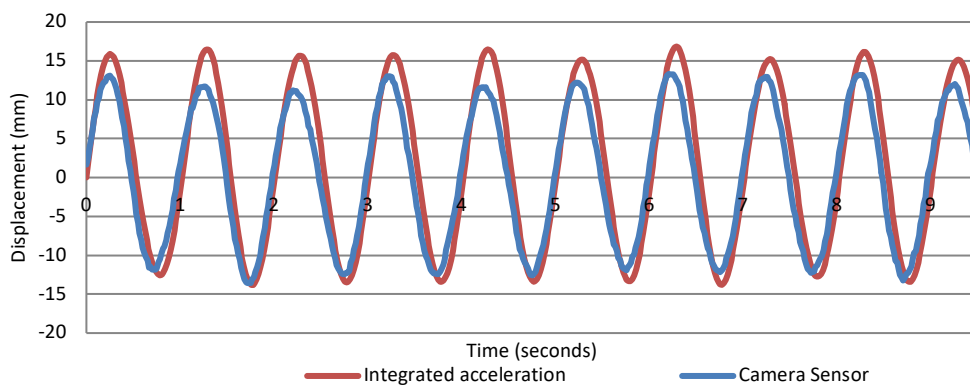

Figure 18 Monitoring location and displacement response to crowd loading

4. Conclusions

This study has detailed the development and field evaluation of a low-cost contactless vision system for remote measurement of structural displacements. The system was evaluated through a comprehensive laboratory and field experimentation whereby a commercially available action camera collected images which were compared with highly accurate displacement measurements obtained using a reference measurement system. The following conclusions can be drawn:

During the laboratory experiments the modified action camera and associated displacement algorithms achieved satisfactory agreements with the chosen reference measurement. The system has been confirmed to provide accurate displacement measurements in field environments, overcoming existing limitations in terms of lighting and power supply requirements. The validation of this system in this study facilitates its use for future monitoring of the Peace Bridge and similar structures, displacement measurement using traditional systems may be cost prohibitive. As the system does not require any target in the structure and is fully battery operated and wireless the potential for rapid deployment on rural sites is particularly promising. Further development of this system will involve the synchronization of several cameras to facilitate wireless multipoint displacement monitoring of civil infrastructure and full modal dynamic analysis.

5. Acknowledgements

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