Development and Application of a Relative Displacement Sensor for Structural Health Monitoring of Composite Bridges

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Abstract: One of the typical bridge construction types on Australia highways is composite bridge consisting of cast-in-situ reinforced concrete (RC) slab supported by steel or precast RC girders. The slab and girders are connected by distributed steel shear links. The shear links are under constant cyclic loadings during bridge operations therefore may experience fatigue damage besides possible corrosion damage and overstressing owing to increased traffic volume and weight. This paper proposes a relative displacement sensor developed to directly measure the relative slip between slab and girder in composite bridges to detect the health condition of shear connections. The structure, design principle, features and calibration of the developed relative displacement sensor are presented. The design of the sensor ensures that there are no voltage outputs for the tension, compression, bending and torsion effects, but only measures the relative displacement between the two connecting pads of the sensor. The accuracy of the developed sensor in measuring the relative displacement response and using it for monitoring the conditions of shear connectors were tested on a composite bridge model in laboratory. The condition monitoring of shear connection under ambient vibrations was conducted. Static loading tests were also conducted to introduce the cracks into the composite bridge besides the damage in shear links. Both the deflections and relative displacements were used for the crack and shear link condition identification. Experimental studies demonstrate that the developed sensor is very sensitive to the relative displacement and has a decent performance for the structural health monitoring of composite bridges.

Keywords: Relative Displacement Sensor; Structural Health Monitoring, Composite Bridges; Shear Connectors; Ambient Vibrations; Crack Detection;

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1. Introduction

Civil infrastructures are continuously exposed to environmental conditions and various external dynamic loads, such as traffic, earthquakes, wind and possible accidental impacts, which result in inevitable structural condition deterioration. Structural health monitoring has become an important research topic for continuous condition assessment and evaluation of structural safety and integrity. Composite structure represents a typical example of bridges on Australia highways. Composite bridges are normally built with cast-in-situ reinforced concrete (RC) slab supported by precast RC or steel girders. Stirrups are embedded in the girders and cast into the slab as shear connectors to link the slab and girders. The shear connection between slab and girders subjects to fatigue and possible corrosion damage, as well as possible overstressing owing to increased traffic weights and volume. Deterioration or break of the shear connection in some regions of the bridge structure causes a loss in the composite action so that the bridge slab and girder respond to traffic loadings independently, resulting in a decrease of the overall rigidity and ultimate resistance of the bridge [1]. As pointed out in [2] that damage of shear connectors will result in shear slippage between the slab and girder and therefore may result in the stiffness reduction up to 17% in a short span bridge.

Vibration based damage detection methods have been used for the condition assessment of shear connectors in composite bridges. It was found that the bridge global vibration parameters such as frequencies, mode shapes and the corresponding mode shape parameters are not sensitive to shear connector condition changes [3]. To overcome these problems, a local detection method has been proposed by directly comparing the frequency response functions of simultaneously measured vibrations on the slab and girder [3]. It was found that the local vibration method would give better identification results than the global vibration methods. However, a large number of sensor measurement locations would be required on the slab and girders. Recently, wavelet based Kullback-Leibler distance [4] and wavelet packet energy [5] have been proposed for damage identification of shear connectors. Liu and De Roeck [6] developed a local condition assessment approach to identify the damage location of shear connectors by using the modal curvature and wavelet transform modulus maxima. Berczynski and Wroblewski [7] validated the numerical models of steel-concrete composite beams with experimental testing results and used later energy transfer ratio to locate the damage in composite beams [8]. Dilena and Morassi [9] studied the damage detection problems with partially degraded shear connection in steel-concrete composite beams. Li *et al*. [10] also presented a damage detection approach by using the concept of transmissibility as it reflects the local change of structures and increases the sensitivity in identifying the damage of shear connectors. All these methods are considered as vibration-based structural health monitoring approaches with different signal processing techniques and featured damage indices.

Damage or failure of shear connectors results in shear slippage and hence relative displacement between girders and slab if the applied load is large enough to overcome the friction force between the girders and slab. The shear slippage between girders and slab depends on the applied load, which makes the bridge response highly nonlinear and difficult to be detected by the traditional SHM method especially when the applied load is small in vibration tests. Therefore the development of a relative displacement sensor as a practical solution to track the shear slippage and failure of shear connectors would be of great interest. As relative displacement is directly related to the shear connector conditions, it is believed to be more sensitive than other response quantities such as acceleration and deformation.

Acceleration response is most commonly used in structural condition monitoring analysis since acceleration is relatively easier to be measured. Displacement is also a good descriptor of the structural deformation behavior and indicator of structural performance, and has been used for structural health monitoring [11]. Traditionally, the displacement can be derived from measured acceleration and strain by using numerical integration algorithms [12, 13]. During the integration process, however, baseline error may be produced if the initial conditions are difficult to be reliably determined as it is usually the case, which then affects the subsequent damage assessment of structures. Linear Variable differential transformer (LVDT) can be used to directly measure the displacements of structures [14], but LVDT is sensitive to temperature effect and only for a limited measurement range. Moreover, the setup of such displacement measurement requires an absolutely stable reference location to place the LVDT, which is not easy to find for in-field tests of civil structures. Recently, laser displacement sensors based on the optical technologies have been developed. The sampling rate of laser displacement sensors may vary from 1Hz to 50kHz, and the measurement range is from about 100mm to 500mm. The laser displacement sensors are also required to be mounted on a fixed foundation and placed very close to the target surface, which may bring significant difficulties in the experimental installation. Besides, the laser displacement sensors are normally costly. Other non-contact displacement measurement methods and equipment have been more intensively researched and developed in recent years based on, e.g. laser Doppler vibrometer [15], GPS [16] and microwave interferometer [17]. Vision-based methods have offered alternatives to displacement measurement of civil structures [18]. Digital image processing system is involved to extract the displacement, which may require a high-resolution camera, a suitable video card, and an intensive computational load on imaging process, such as pixel scanning, object identification and images correlation. The above-mentioned displacement measurement technologies are developed to measure the absolute displacement of targets. To obtain the relative displacement of structures, which is more directly related to local structural damage, multiple numbers of equipment are required for simultaneous measurements and post measurement data processing is needed to derive the relative displacement.

For the purpose of measuring relative displacement, most current studies focus on determining the relative movement of structure components, of its foundations, surrounding ground, and adjacent buildings. At present, such monitoring on the relative movement is mainly implemented by a variety of sensors, such as networks of optical targets installed over the structure to measure deformations and inclinometers to measure rotations. The relative displacement between different floors of building structures is an important indicator of structural performance and index for post-event damage assessment [19]. Hutchinson and Kuester [20] adopted a vision based approach for measuring earthquake-induced structural displacement, such as inter-story drift. Kanekawa *et al.* [21] proposed to use the phototransistor array to measure the relative inter-story displacement for building structures. The proposed system has a resolution of 0.1mm and a sampling rate up to 100Hz. Myung *et al.* [22] proposed a multi-pair structured light system for displacement measurement of structures. The system comprises of two cameras and laser displacement sensors, and is able to measure the relative displacement between any two locations on the structure. The detailed review on the techniques for the measurement of relative displacement can be found in [23]. Most approaches to measure the relative displacement are based on vision technologies and image processing techniques. The build-up of such systems may require a high cost and complicated experimental setup with a series of cameras or similar photogrammetry devices. The applicability of such approaches may suffer owing to the uncertain environment, for example, fog or obstacles to block the scanning field of cameras. Moreover, due to the inaccessibility of some structural components, measuring the relative displacement may not be achieved.

This paper presents a relative displacement sensor developed to directly measure the relative displacement between slab and girder in composite bridges. The developed sensor is very sensitive to the relative movement between two points on the structure, and is also easy to be directly mounted on the structure. It does not require a stable reference point therefore it is easy to setup and is cost-effective to measure the relative displacement. It can be used for real-time structural health monitoring. The structure, design principle, features and calibration of the developed relative displacement sensor are presented. Relative displacement is measured from four strain gauges stuck on a square component connecting two pads, which are used to fix the sensor on the testing structure. The output voltage due to the shear distortion is calculated based on the principle of Wheatstone bridge circuit. The design of the sensor ensures that there are no voltage outputs for the tension, compression, bending and torsion effects. The experimental calibration of the sensor is performed between the measured strain and output relative displacement. Experimental studies are conducted to demonstrate the sensitivity and performance of the developed relative displacement sensor in condition monitoring of shear connectors in composite bridges. The sensitive radius of the sensor to detect the damage of shear connectors is investigated. The on-line monitoring of shear connection conditions under ambient vibrations is conducted. The relative displacement sensor is also applied for crack identification in static loading tests and the performance is compared with the traditional measured vertical deflections.

2. Design and Calibration of the Developed Relative Displacement Sensor

A relative displacement sensor is developed based on the principle of Wheatstone bridge circuit and it can be used to measure the relative displacement between two points on a structure. Four strain gauges are stuck on a square component connecting two pads, which are used to fix the sensor on the testing structure, to construct a Wheatstone bridge circuit. The relative displacement is derived from the measured strain. Following sections will introduce the sensor design, features and calibration.

2.1. Sensor Structure

Figure 1 shows the structure of the developed relative displacement sensor. The sensitive component of the sensor is a square metallic plate of 15mm×15mm. Two pads at the ends are used to fix the sensor to target structures with four 8mm diameter screws. The relative displacement between these two locations is measured. The square metal plate in the center is 1mm thick, thin enough to reduce the effect of thickness on the accuracy of the sensor and avoid the sensor affecting the local stiffness of structure. The sensor plate is made of aluminium, which means that the stiffness of the developed relative displacement sensor is much lower than that if made of steel. Compared with a civil engineering structure, the developed sensor is of a very small size and stiffness. Therefore placing such sensors on civil structures is not likely to significantly change the natural dynamic properties of structures. Owing to the negligible mass of the sensor as compared to the structure, e.g., a bridge, prominent dynamic interaction between sensor and bridge is also unlikely. The dimensions of the sensor are shown in Figure 2. The sensor measures shear distortion of the metal plate owing to relative displacement of the two locations that the two end pads of the sensor are fixed to, which occurs along the horizontal direction (axis x), by means of an array of four strain gauges arranged on the metal plate as four diagonal arms of a Wheatstone bridge, as shown in Figure 3. The design principle and features of the developed relative displacement sensor will be described in the following sections.

2.2. Sensor Design Principle

The four arms of the bridge in Figure 3 are denoted by the resistors R_1 to R_4. They are placed in diagonal directions, in which R_1 to R_3 are placed in the same direction, and R_2 to R_4 are in the other diagonal direction. The output voltage of the full bridge is calculated based on the principle of Wheatstone bridge circuit as

$$\frac{v}{U}=\frac{1}{4}\left(\frac{\Delta R_1}{R_1}-\frac{\Delta R_2}{R_2}+\frac{\Delta R_3}{R_3}-\frac{\Delta R_4}{R_4}\right) \tag{1}$$

where v and U are output and input voltages, respectively. ΔR_1, ΔR_2, ΔR_3 and ΔR_4 are the resistance variations of the four resistors R_1, R_2, R_3 and R_4, respectively.

The relationship between the relative change of a strain gauge and the strain is described as

$$\frac{\Delta R}{R}=k\cdot\varepsilon \tag{2}$$

where k is the gauge factor, which is about 2 for metal strain gauges. Substituting Equation (2) into Equation (1) for the four strains, we have

$$v=\frac{1}{4}\cdot k\cdot U\cdot(\varepsilon_1-\varepsilon_2+\varepsilon_3-\varepsilon_4) \tag{3}$$

where $\varepsilon_1, \varepsilon_2, \varepsilon_3$ and ε_4 are strains of four resistors R_1, R_2, R_3 and R_4, respectively. Equation 3 shows that base values of R_1, R_2, R_3 and R_4 are not important as long as the gauge factors are equal.

2.2.1. Shear Distortion

A relative displacement d along the x-axis (Figure 3) will deform the four strain gauges differentially due to the diagonal orientation so that the relative displacement appears as shear distortion of the plate. For diagonal deformation we have

$$\varepsilon=\varepsilon_1=-\varepsilon_2=\varepsilon_3=-\varepsilon_4 \tag{4}$$

Substituting Equation (4) into Equation (3), the output voltage due to the shear distortion is

$$v=\frac{1}{4}\cdot k\cdot U\cdot(\varepsilon_1-\varepsilon_2+\varepsilon_3-\varepsilon_4)=k\cdot U\cdot\varepsilon \tag{5}$$

From Equation (3), the output voltage is linearly proportional to the strain ε and hence the relative displacement d for a given input voltage and a constant strain gauge factor. The supplying input voltage for the developed sensor is 2.5V in the study. An experimental calibration test is necessary to find out the constant K in the following relationship between the strain and relative displacement

$$d = K \cdot \varepsilon \tag{6}$$

where K is a coefficient to define the linear relationship between strain and relative displacement.

2.2.2. Tension and Compression Effect

The target of the developed sensor is to measure the relative displacement along the horizontal direction between the two pads. However, the sensor may suffer the adverse effects, such as tension/compression, bending and torsion due to the complicated loading condition on the structure. In order to minimize these effects and improve the performance of the sensor to detect the relative displacement, a symmetry behavior of the Wheatstone bridge circuit is used.

A tension or compression occurred along the x- or y-axis of the sensor as shown in Figure 2, will produce the same strain on all strain gauges i.e.

$$\varepsilon = \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 \tag{7}$$

Then by Equation (3), we have

$$v = \frac{1}{4} \cdot k \cdot U \cdot (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) = 0 \tag{8}$$

This means that the tension and compression of the sensor will produce no output.

2.2.3. Bending and Torsion Effect

When there is a bending effect along x-axis or a torsion effect rotating with x-axis direction, the following relationship on the strains can be derived based on the symmetry of the design circuit with

$$\varepsilon_1 = \varepsilon_2, \quad \varepsilon_3 = \varepsilon_4 \tag{9}$$

The strains due to the bending effect along y-axis and the torsion effect rotating with

y-axis have the following relationship

$$\varepsilon_1 = \varepsilon_4, \quad \varepsilon_2 = \varepsilon_3 \tag{10}$$

For both cases, due to the symmetry and by Equation (3), the output voltage due to the bending and torsion effect is zero. Under the ideal conditions when the tension or compression, bending and torsion occur along the x- or y-axes of the sensor, only the shear displacement will be detected in the required direction.

2.3. Sensor Calibration

This section describes the experimental calibration procedure used to determine the constant K in Equation (6). It could be possible to derive the coefficient K theoretically. However, uncertainties existed in the materials and dimensions, such as non-uniform properties in the thickness, Young's modulus and density, etc., might make the theoretical K value lose the accuracy for use as baseline information in the initial stage of this sensor development. To avoid this problem associated with the unavoidable uncertainties, the experimental calibration test was used to determine the coefficient K, which could be more reliable and accurate for experimental applications [24].

If we define $y(x)$ as the output of a relative displacement sensor which can generally be expressed as the sum of a straight line having a slope of K and the error $g(x)$ from the straight line. The function $y(x)$ is expressed as

$$y(x) = K \cdot x + g(x) \tag{11}$$

in which, x is the measured strain. Let the measured data from the relative displacement sensor at the sampling position x_i be $y(x_i)$, the relative error of the calibration is defined as

$$RE = \frac{\left\|\{y(x_1) - K \cdot x_1, y(x_2) - K \cdot x_2, \cdots, y(x_n) - K \cdot x_n\}\right\|}{\left\|\{y(x_1), y(x_2), \cdots, y(x_n)\}\right\|} \times 100\% \tag{12}$$

where n is the number of measured data used for calibration.

Figure 4 shows the sensor mounted on a rigid flat plate fully fixed at the bottom and allowed to slightly slide at the top where a relative deformation is induced and measured by a micrometer. The least-squares method is used to best fit these data with a straight line and calculate the coefficient K. Figure 5 shows the introduced relative displacement on the sensor vs output micro-strain from the Wheatstone bridge. The slope, that is the coefficient K, can be used to convert measured strain from the sensor as relative displacement when installed on a structure. Most points are fitted well with a clear linear relationship as shown in Figure 5. The relative error is calculated as 7.4%. The error in the calibration is probably due to the measurement inaccuracy in the micrometer with the resolution of 0.1mm and in strain measurement system besides the noise effect in measured signals. Unfortunately we do not have a more sensitive equipment to give a better relative displacement measurement. Nevertheless a linear behavior can be observed to demonstrate the relationship between strain and displacement. Moreover, it should be noted that the relative displacement sensor is developed to detect the damage of shear connectors through shifts in relative displacement between two structural points. In practice, the relative displacement between bridge girder and deck under traffic loading is expected larger than 0.1 mm at locations with damaged shear connectors. In this paper, the application of the developed relative displacement sensor is demonstrated by measuring the relative displacement between slab and girder in composite bridges for structural health monitoring.

3. Health Monitoring of Composite Bridge

Experimental studies on a composite bridge model in laboratory are conducted to verify the accuracy and investigate the performance and sensitivity of the developed relative displacement sensor for the structural health monitoring of composite bridges by tracking the shear connection conditions. A composite bridge model was constructed with a RC slab supported on two steel girders. Sixteen shear connectors were mounted with equal spacing in each girder to link the slab and steel girders. The dimensions of the model are shown in Figure 6. The length is 3.16m and the width is 0.55m. The height of steel beam and the thickness of slab are 0.15m and 0.065m, respectively. The slab constructed with Grade 40 concrete was connected to two 150UB14 universal steel girders by shear connectors. The shear connectors connecting the slab and girder are denoted as SC1 to SC32. The bridge was located on two steel frames which are fixed to the laboratory strong floor. In this study, the design of shear connectors allows for simulation of the failure of specific shear links as well as for resetting to the undamaged state. Therefore, bolts screwing into metric nuts cast in the slab were used to work as shear connectors. The nuts were welded onto the reinforcement bar in the slab before pouring. Figure 7 shows the design of shear connectors and the composite bridge model. If all bolts are engaged in the nuts and tightened, the structure condition corresponds to the undamaged state. The damage of shear connectors is introduced into the structure by unscrewing several specific metric bolts to simulate the failure of shear links. It may be noted that the bolt is fully unscrewed from the metal nut to simulate the failure of shear link in this study. It is interesting to study the detection problems with partially damaged shear connectors, however, this is difficult to perform in the experimental tests. If a shear link or a bolt in this study is not completely removed, to create relative movement between deck and girder, large shear deformation of the bolt or concrete crushing damage around bolt needs be induced. Such damage could occur in a real bridge under traffic loading, but it is not likely in the lab tests under small loading and vibrations. This is the limitation of the tests. The identification with different damage servilities of shear connectors is not conducted in this paper.

Four relative displacement sensors were fabricated and mounted on the bridge model. As shown in Figure 2, the mounting plates are much thicker and wider than the sensor plate where the strain gauges are placed. The vibration modes of the mounting plates are well away from the sensor plate and coupling effect is not likely. Moreover, the vibration frequencies of the sensor are much higher than those of civil structures. The effect of tension/compression, bending and torsion of the sensor plate itself has been studied in Section 2 and it has been found the sensor would not measure those responses. Figures 8(a) and (b) show the experimental model and a developed sensor prototype installed on the bridge, respectively. One end of the sensor is fixed on the steel girder, and the other end on concrete slab. Such installation manner is much easier than vision-based approaches, which need to setup a number of cameras or other optical devices, and easier than LVDT measurement approach which needs a fixed reference point. Moreover, the inaccessibility of the interface between slab and girders makes the setup of cameras and LVDT difficult. This also demonstrates the advantages of the developed relative displacement sensor to directly install it on the bridge and track the behavior of shear slip. A National Instruments (NI) dynamic data acquisition system was used for data recording and quick in-situ analysis. The system is able to measure acceleration, displacement and strain synchronously. Figure 9 shows the locations of placed relative displacement sensors. The relative displacement sensors are defined as S1, S2, S3 and S4. The relative displacement sensors are placed in the center of two shear connectors, for example, S1 is placed in the center of SC1 and SC2. It may be noted that S1 and S4 are located close to supports.

3.1 Verification on Accuracy of the Relative Displacement Sensor

A trolley was designed in the laboratory with two concrete blocks placed on it. The trolley was placed on the top of the bridge model as shown in Figure 10(a). Two laser displacement sensors were also installed to target at the two pads of S1, as shown in Figure 10(b), in order to calculate the relative movement between two pads and validate the accuracy of the relative displacement sensor. The difference between the measured displacements from these two laser displacement sensors is obtained and compared with the directly measured relative displacement by the developed sensor.

Relative displacements from the laser displacement sensors and relative displacement sensor were measured when the trolley is pulled by a crane to move off the bridge model. Figure 11 compares the measured relative displacements by the laser displacement sensors and relative displacement sensor. The behavior of the relative displacement can be tracked and a good agreement between these two measurement approaches is observed, which validates the accuracy of the developed relative displacement sensor. As shown measurements from the laser displacement sensors give a slightly smaller relative displacement compared with the relative displacement sensor. The reason that using two laser displacement sensors is believed to give less accurate relative horizontal displacement (slip between girder and deck) measurement is because vertical deformation of the bridge model under loading will change the focus points of laser measurements. This problem actually always occurs when using non-contact optical measurements of structural displacement. However, this is not a problem in the developed relative displacement sensor because it is attached to the two measurement points and moves with them in all the directions. Therefore it is believed that the relative displacement sensor will give more accurate measurements with less noise effect as observed in Figure 11.

3.2 Damage Detection of Shear Connectors

Many bridges are built as composite structures in Australia and elsewhere in the world with a short- or medium-span configuration. In such bridges, shear connectors are provided to link the slab and girders to resist the shear forces between slab and girders as described above. The break or damage of shear connection will cause a significant relative slip between the slab and girder and loss of stiffness and load-carrying capacity of the bridge [25]. The developed relative displacement sensor can track such behavior, and be used for monitoring the conditions of shear connectors in composite bridges. The relative displacement at the interface between the slab and girder of a composite bridge is measured for the condition assessment.

In laboratory test, the sudden damage of shear connector is introduced by releasing the shear bolt SC1. The measured relative displacement responses were processed to investigate if the occurrence and location of the damage can be identified. Figure 12 shows the measured responses from the four relative displacement sensors. It can be observed from Figure 12(a) that there is a significant relative displacement shift at about 11s, which clearly indicates the occurrence and moment when the shear connector SC1 is released. The shear slip between slab and girder is as small as 0.04mm. The developed relative displacement sensor accurately detects the shear slip and identifies the failure of shear connector. If using the optical technologies with vision-based approaches, extremely high resolution cameras will be required as the relative displacement is very tiny, which will make the experimental setup and solution very expensive. The application of double integration methods with accelerations to get the displacement is also not feasible since the errors in the integration process will flood the small relative displacement change and true damage information. Sensors S2, S3 and S4 are quite far away from the damage location (SC1). Therefore as shown in Figure 12(b), (c) and (d) the shift in the measured response is not clear enough to confidently identify the damage. These observations identify the possible region of the damage location (close to S1 based on the observed significant relative displacement change) and indicate the sensitivity range of the relative displacement sensor is limited. The damage of shear connectors can be detected only when the relative displacement sensor is close to the damage. The sensitivity radius will be investigated and discussed in the following section.

3.3. Sensitivity Radius of the Developed Relative Displacement Sensor

The above testing results indicate that the developed relative displacement sensor can identify the damage of shear connector if it is placed close enough to the damaged connector. This section investigates the sensitivity radius of the relative displacement sensor for monitoring the shear connector conditions.

In order to investigate the sensitivity radius of the sensor to detect the failure of shear connector, a series of experimental tests with shear connectors SC2, SC4, SC6 and SC8 released separately were conducted. Relative displacement responses measured by S1 and S2 in those tests are shown in Figures 13 and 14, respectively. It should be noticed that S1 is placed close to support location and S2 far away from the support. As shown in Figure 13, the signal shift at the moment when the shear connector is released becomes smaller with the increasing distance from the sensor to the damaged shear connector. The output relative displacements can successfully reflect the change due to the damage of shear connectors when releasing SC2, SC4 and SC6 as shown in Figures 13(a), (b) and (c) respectively. The measured response almost fails to detect the damage when SC8 is removed as evidenced in Figure 13(d) with an unobvious shift. This observation is expected because the relative displacement sensor measures the local relative movement and can only track the conditions of shear connectors locally. This sensitivity study shows that the developed relative displacement sensor can identify the conditions of shear connectors within around 0.5m-0.9m, where the detection within 0.5m is more reliable.

It is interesting to see the sensitivity radius if the sensor is placed far away from the support location, i.e. S2 in the bridge center. Figure 14 shows the relative displacement changes in S2 when releasing shear connectors SC2, SC4, SC6 and SC8 separately. It is observed in Figure 14 that the sensor is able to detect the damage when releasing SC6 and SC8 and fails to detect the damage in SC2 and SC4, which indicates that the sensitivity radius is 0.3m if the sensor is placed in a least sensitivity location for measuring relative displacements. Since the shear forces at support locations are much larger than that in the bridge center in terms of such a simply-supported composite bridge, it is expected that the relative displacement at the support location has a more sensitive performance to the shear connection changes. This is the reason why S1 at the support has a lager sensitivity radius than S2 at the center.

Combining the observations in Figures 13 and 14, specifically the developed sensor has a sensitivity radius as 0.5m-0.9m at critical location and 0.3m non-critical location. However, it should be noted that these observations are only based on the current model and testing conditions. If a larger loading, i.e. moving load is applied, a more significant relative displacement is expected and the sensitivity range of the sensor is expected to be longer. On the other hand, if the friction between the girder and slab is larger, the relative displacement will be smaller and the sensitivity range will also be smaller.

3.4. Online Structural Health Monitoring under Ambient Vibrations

Online structural health monitoring is essential for civil infrastructures and can quickly indicate the change of structural behavior and performance. Experimental studies will be conducted in this section to monitor the conditions of shear connectors when bridge is subjected to ambient vibrations. An exciter was placed on the bridge deck at the quarter-span distance to left support as shown in Figure 15, and white noise excitations were generated from the exciter to the bridge. Four accelerometers were placed at the same locations as relative displacement sensors and they are correspondingly defined as A1, A2, A3 and A4. Both the relative displacements and acceleration responses were measured for the online health monitoring. Shear connector SC1 was removed firstly and SC16 is followed during the test. It may be noted that SC1 is close to relative displacement sensor S1 and SC16 near S4.

Previous studies demonstrate that a perturbation or spike in the wavelet coefficients could be observed in the wavelet transform diagram and it indicates the moment when the structural condition change occurs [26, 27]. Therefore continuous wavelet transform of the measured acceleration responses is performed to investigate if the damage of shear connectors can be identified. Figure 16 shows acceleration measurements and their continuous wavelet transform diagrams from four acceleration responses. It can be seen from Figures 16(a), (b), (c) and (d) that neither one of the four measured accelerations can detect the change of conditions of shear connectors. It has been studied that acceleration measurements under ambient vibrations can be used to detect the damage of shear connectors in composite bridges [28], a number of vibration measurements are simultaneously required on the slab and girder and the cross-correlation functions are calculated between the vibrations on the slab and girder. Specific signal processing techniques are required to extract a sensitivity feature to reflect the local damage of shear connections, i.e. the change in the percentage of selected wavelet packets energy to the total wavelet packet energy of the cross-correlation function [28]. It is noted that a large number of sensors or repeated tests would be required to achieve the enough measurement locations on slab and girders in the above-mentioned method. However, in this study, the measured relative displacements from S1 and S4 clearly indicate the occurrences and instants of the shear connector damage, as shown in Figure 17. An obvious sudden change in the measured response from S1 at 12s and following a significant shift in the measured response from S4 at 25s are observed, which indicate that the introduced damages of shear connectors are monitored correctly. No clear information relevant to the damage can be observed from the measured responses at S2 and S3 as they are out of the sensitivity radius and therefore are not able to track the damage of shear connectors at SC1 and SC16. The signal-to-noise ratio of sensors S1 and S4 are 13.1dB and 14.4 dB, respectively. This study demonstrates that only a few relative displacement sensors can effectively and accurately identify the occurrences, instants and possible regions when the damages of shear connectors are introduced.

4. Static Loading Test

The composite bridge model was statically loaded until intensive cracks appear on the concrete slab. Two loading scenarios were carried out, and the loading force was applied with the two-point static load in the center of the bridge. Figure 18 shows the experimental setup for these two loading scenarios. A 20ton load cell was used to measure the applied load. Three laser displacement sensors were placed to measure the vertical deflection of the bridge, and they are denoted as D1, D2 and D3. It should be noticed that D1, D2 and D3 were placed in the same cross sections as the relative displacement sensors S1, S2 and S3, as shown in Figure 9. In each loading scenario, the vertical deflections of the bridge model and relative displacements between girder and slab were measured to check if these measurements can be used for detecting the crack occurrence.

4.1. First Loading Scenario

Figure 19(a) presents the load-vertical deflection curve of D2 for the loading and unloading processes in the first loading scenario. The load is gradually increased to 122 kN. The load-vertical deflection curve within 80 kN is mainly linear-elastic. A notable change is observed around 85 kN with a significant increase in the measured vertical deflection from D2, which corresponds to the occurrence of cracks. The same behavior is observed in the load-relative displacement curve of S2, as shown in Figure 19(b). These notable changes are highlighted with red circles in figures. It can be observed that there are several small oscillations in the relative displacement as shown in Figure 19(b) when the static load is equal to 105 kN. These show the growth of the existing cracks due to further increasing loading applied on the bridge model. Figure 20 shows that a longitudinal crack is observed in the middle of the cross-section of the slab because the stiffness of steel girders is very strong in this bridge model. The concrete slab is supported on two strong steel girders, which is the reason why the longitudinal crack is observed. A significant increase in the vertical deflection of the bridge is evidenced due to the crack. It can be noticed that the final displacement after unloading is about 8mm and the relative displacement 0.13mm as the bridge has been damaged with permanent deformations. Both the vertical deflection and relative displacement are capable of identifying the occurrence of such cracks. However, the relative displacement is more sensitive for identifying the growth of exiting cracks than vertical deflection.

4.2. Second Loading Scenario

The damaged bridge model was reloaded in the second loading scenario. Figure 21(a) and 21(b) show the load-vertical deflection and load-relative displacement curves of D2 and S2, respectively. The applied load is gradually increased to 140 kN in this case. Two slight changes which are highlighted with red circles in these loading-deformation curves are observed due to the formation of cracks at about 130 kN. These changes are zoomed with the same scale and it can be observed that relative displacement changes are more significant than vertical deflection. Figure 22 shows the additional shear cracks observed in the region from shear connectors SC13 to SC16 and from SC29 to SC32. As those cracks are associated with damage of shear connections, the relative displacement is observed to be more sensitive to reflect and identify the damage with a relatively larger slip between slab and girder as demonstrated in Figure 21(b). The above studies demonstrate that the developed relative displacement sensor can effectively detect the cracks in the composite bridge besides the damage in shear connections.

5. Discussions

The presented displacement measurement approach in Reference [29] is based on that the vibration displacement can be expressed in terms of an infinite number of vibration modes and be related to the measured strains through the strain-displacement relationship of a beam structure. The relative displacement can be obtained from the displacement of tip of a cantilever beam with respect to its support. Multiple vibration modes can be considered to achieve a good accuracy with this technique. If more vibration modes are included, more sets of strain gauges are needed. Moreover, the locations of placed strain gauges require to be selected carefully to reduce the measurement error. Compared with the beam-based measurement techniques, the proposed relative displacement sensor can basically capture all significant vibration modes of the target structure and be placed at an arbitrary location of interest. Besides, the experimental setup for beam-based measurement techniques could be very difficult for inaccessible interfaces between the slab and girder in composite bridges. The developed sensor can be easily installed on the structure to measure the relative displacement of the target location in a cost-effective and reliable manner, and this is an advantage of the proposed relative displacement measurement approach.

It is admitted in Section 2.3 that the theoretical sensitivity value can be derived based on the finite element analysis of the designed sensor. However, many uncertainties may exist in the finite element modelling including stiffness, mass and boundary conditions. Model updating may be required to achieve an accurate model to derive the coefficient K in Equation (6). Errors in manufacturing may also affect this coefficient value. Therefore experimental calibrations are conducted instead of numerical analysis to calculate the coefficient K between relative displacements and strains, which could be more reliable and accurate for experimental applications. Future studies may focus on the comparison between theoretical and experimental values.

6. Conclusions

A relative displacement sensor is developed to directly measure the relative slip between slab and girder in composite bridges for structural health monitoring. The structure, design principle, features and calibration of the developed relative displacement sensor are presented. The accuracy of the developed sensor has been verified by comparing the measured relative displacement with that derived from laser displacement sensors. The sensitivity radius of the developed sensor in monitoring the shear connections is investigated. The application of the developed relative displacement sensor has been demonstrated to monitor the damage of shear connectors in a composite bridge model. Online monitoring and crack detection are conducted. The measured relative displacement can effectively and accurately identify the damages of shear connectors under ambient vibrations and shows a superior performance than acceleration measurement. The relative displacement can effectively detect the cracks in the composite bridge besides the damage in shear connections.

Experimental investigations have demonstrated that the developed sensor is very sensitive to the relative displacement response and has a decent performance for the structural health monitoring of composite bridges. The developed relative displacement sensor does not require a fixed reference point and can be directly installed on the target structure that is easy to setup. Another advantage is that the sensor is cost-effective, reliable and capable of performing various structural health monitoring purposes. The developed sensor has many potential applications in different structure types for structural health monitoring.

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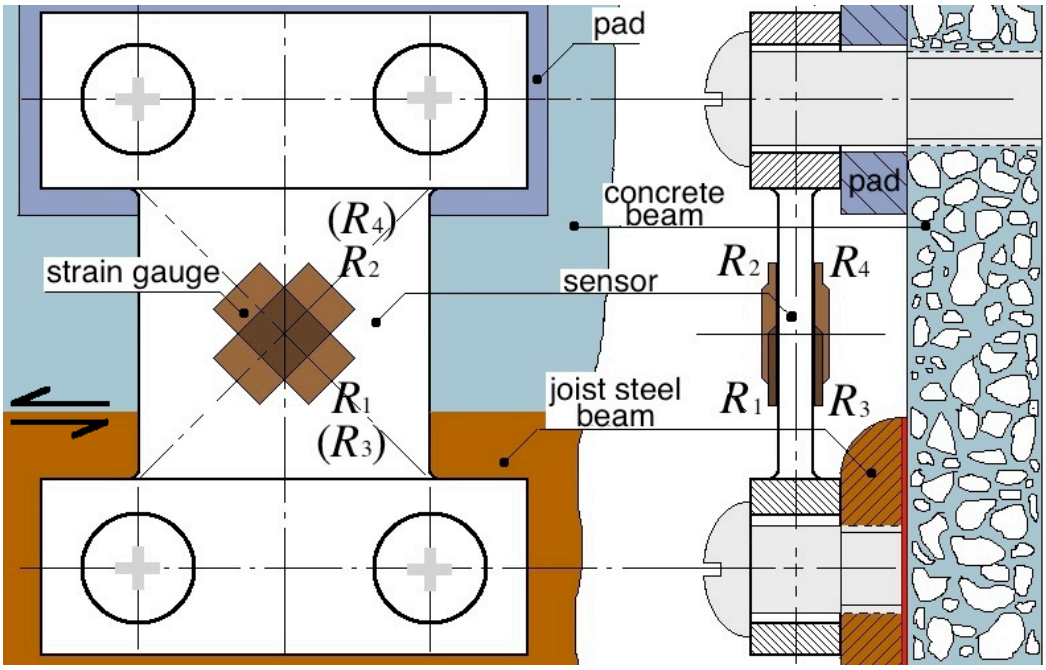


Figure 1 - Schematic setup of the developed relative displacement sensor

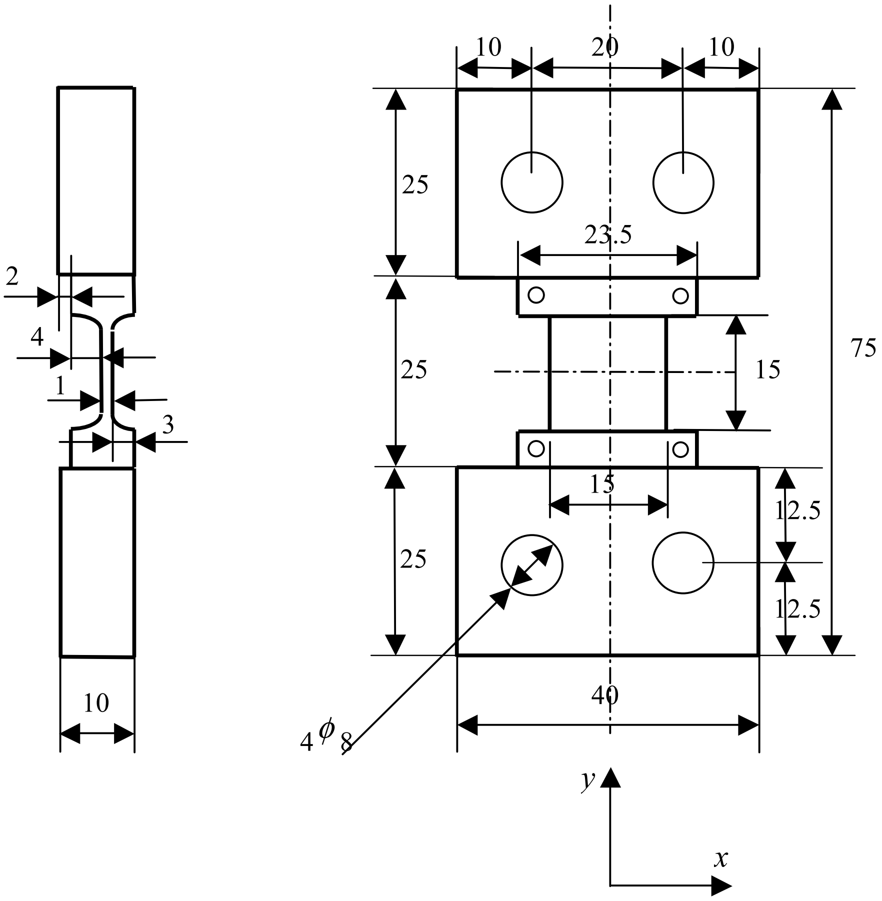


Figure 2 - Dimensions of the developed relative displacement sensor (unit: mm)

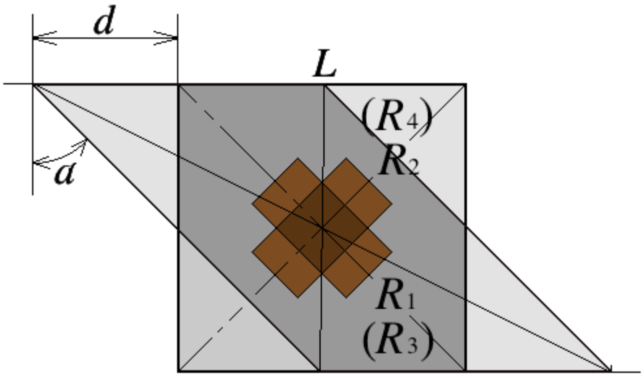


Figure 3 - Schematic shear distortion design of the bridge circuit: (a) Schematic shear distortion on the sensitive component of the sensor, (b) Wheatstone bridge circuit (Full bridge)

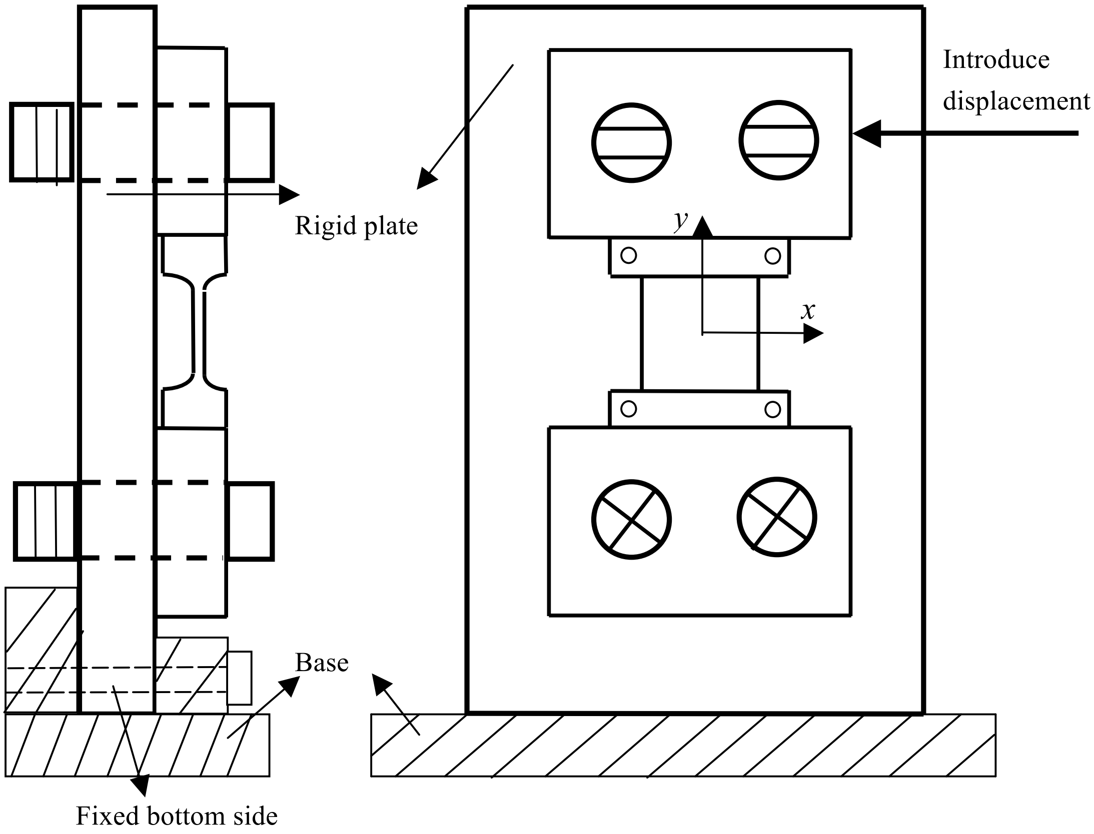


Figure 4 - A platform used to calibrate the sensor sensitivity

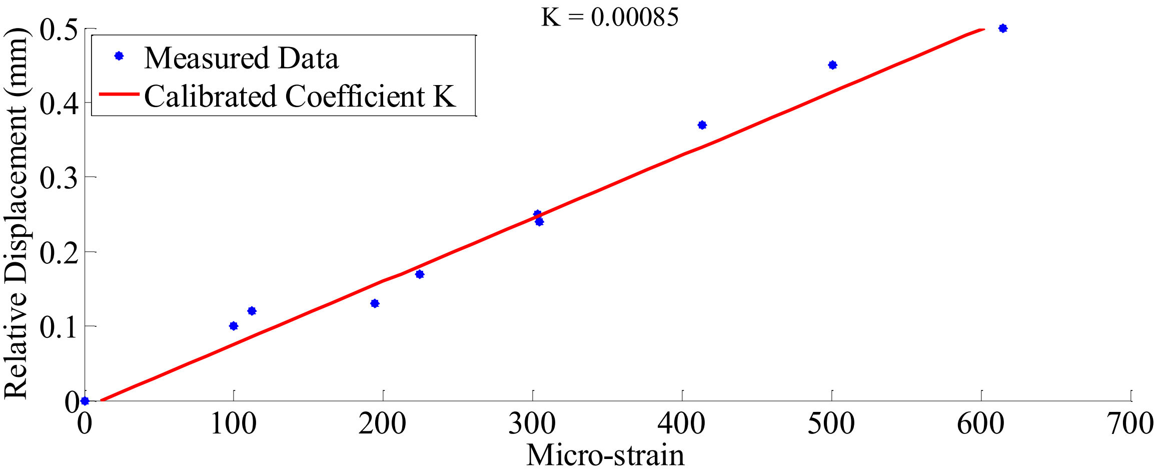
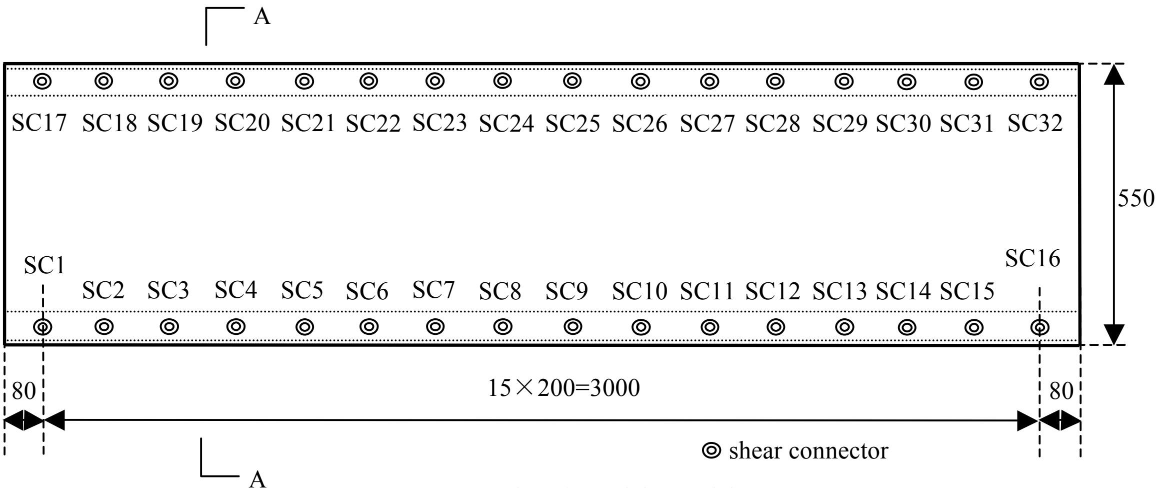
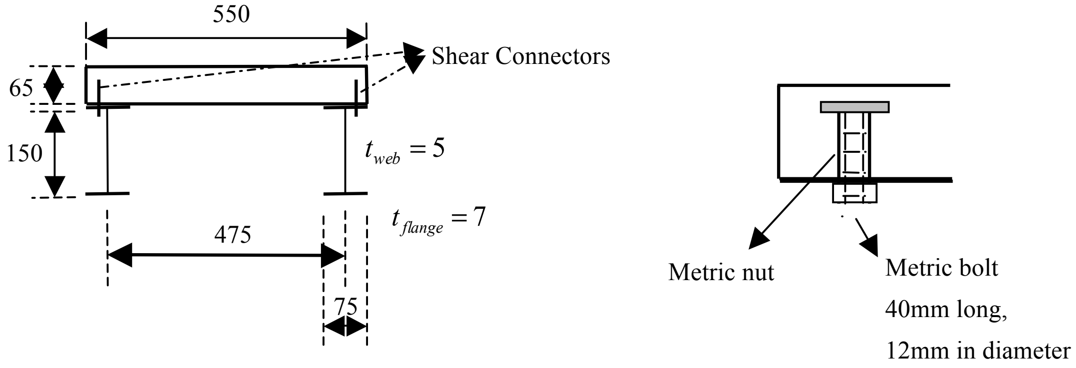


Figure 5 - Sensor calibration between strain and displacement



(a) Plan view of the model



(b) Cross section of the model (A-A)

(c) Shear connector

Figure 6 - Dimensions of the composite bridge (unit: mm)

(a) Metric bolt and nut

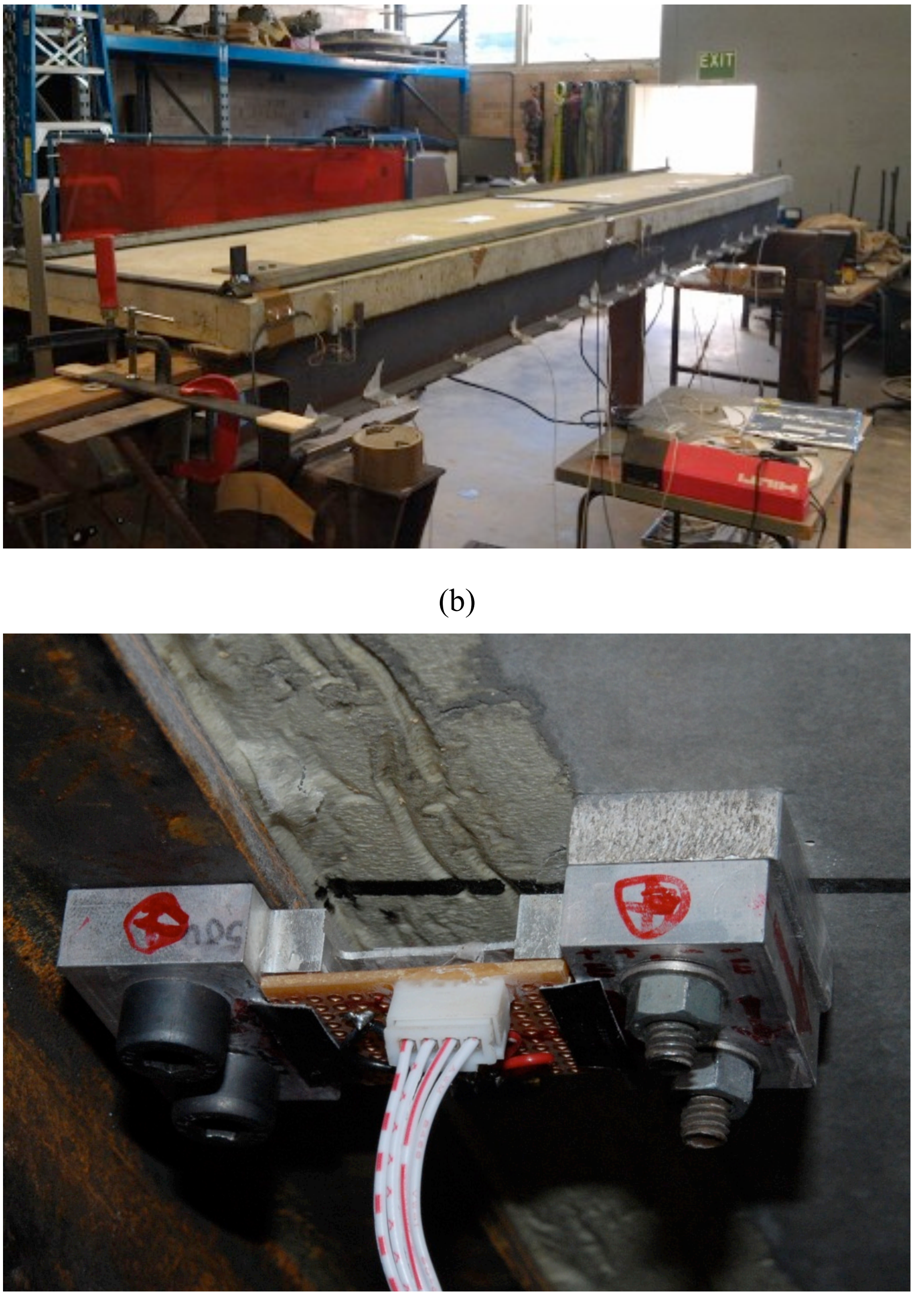
(b) Bolt screwed into the nut

(c) Plan view of shear connectors before pour

(d) Shear connector in the structure

Figure 7 - Design of shear connectors and composite bridge

(a)



(b)

Figure 8 - Experimental setup (a) Composite bridge. (b) Sensor prototype

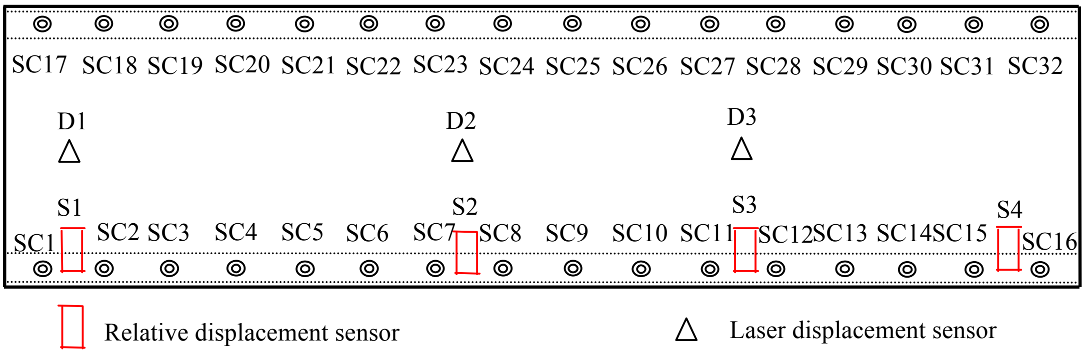


Figure 9 - Locations of relative displacement sensors

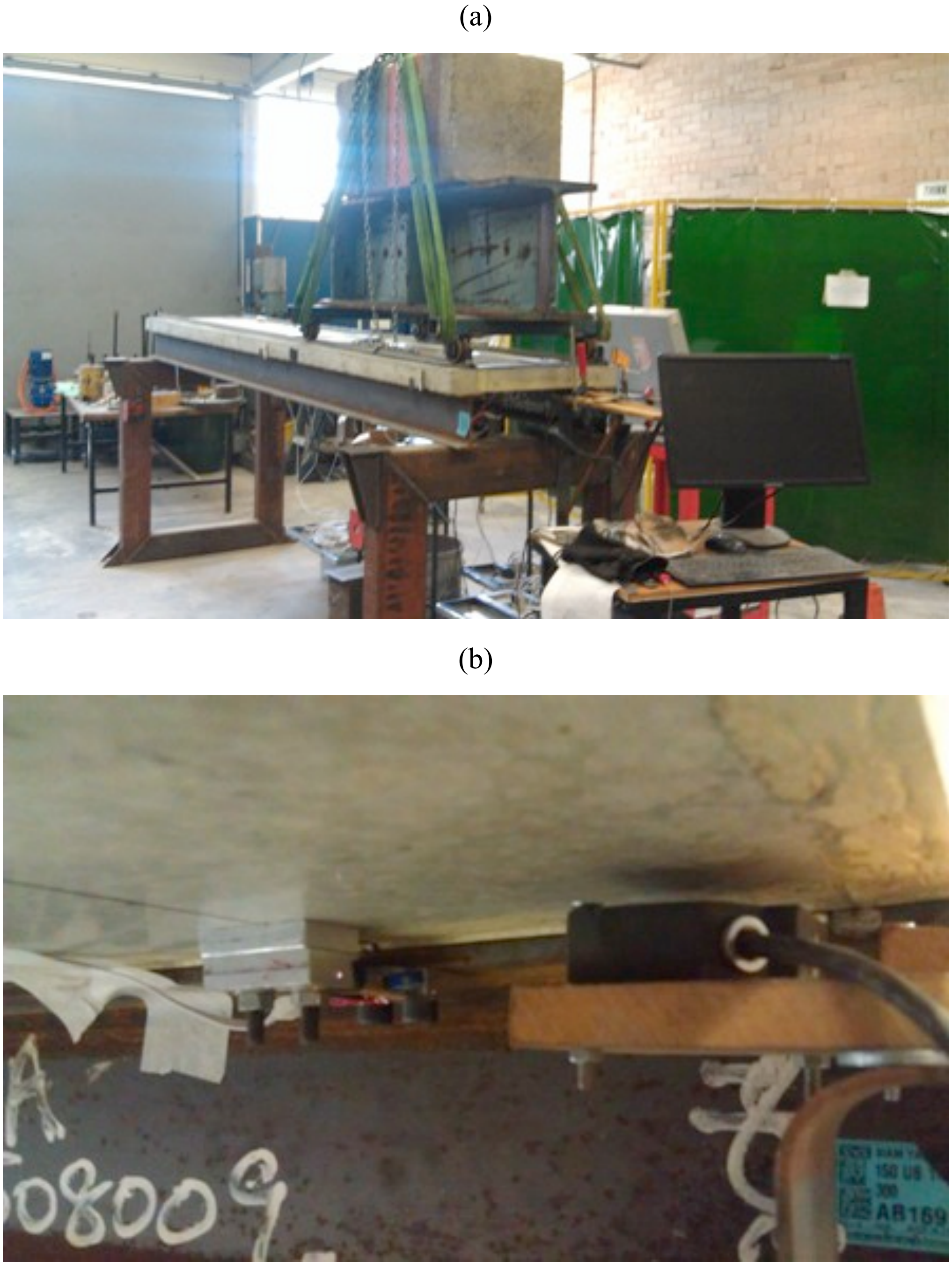


Figure 10 - Experimental test for the accuracy verification of the sensor

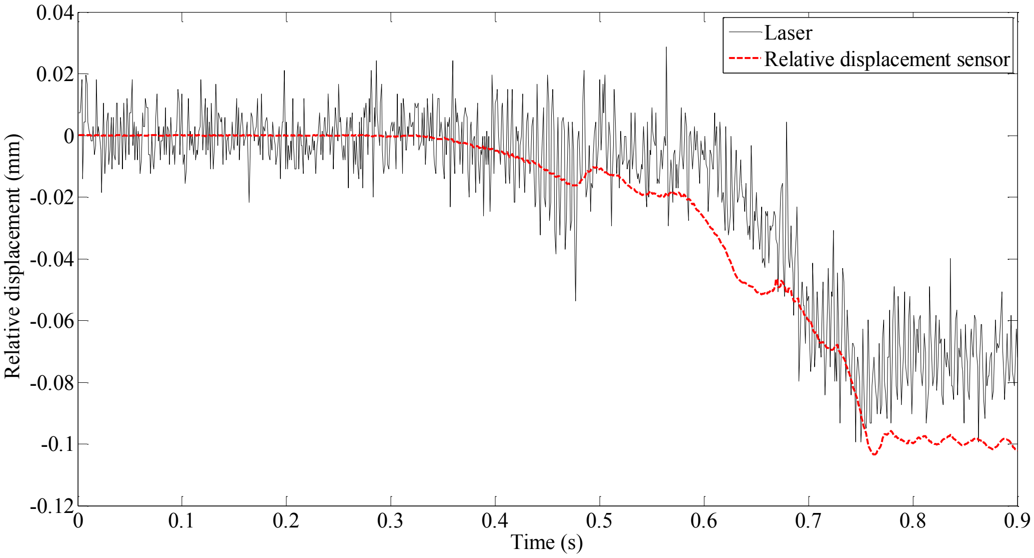
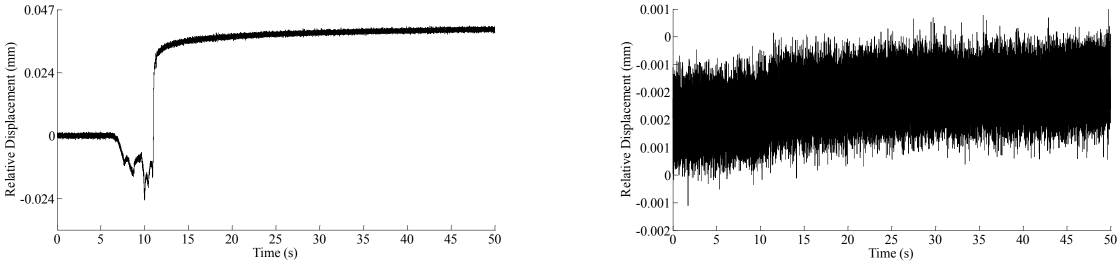
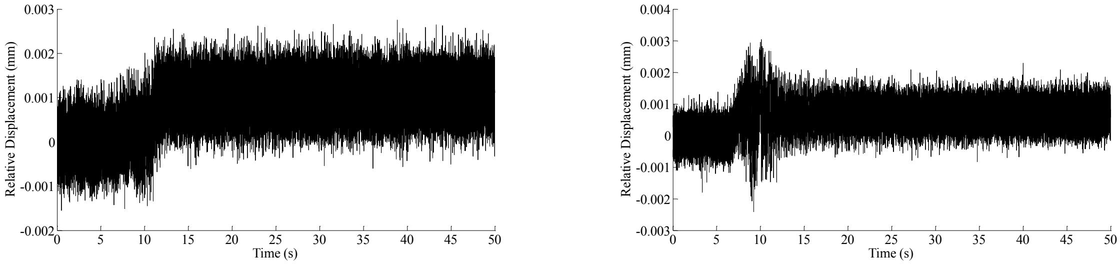


Figure 11 - Measured relative displacements from lasers and developed sensor

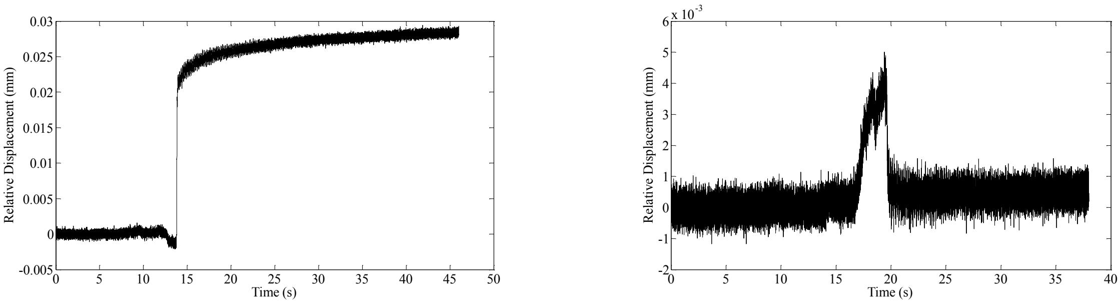

(a) S1

(b) S2


(c) S3

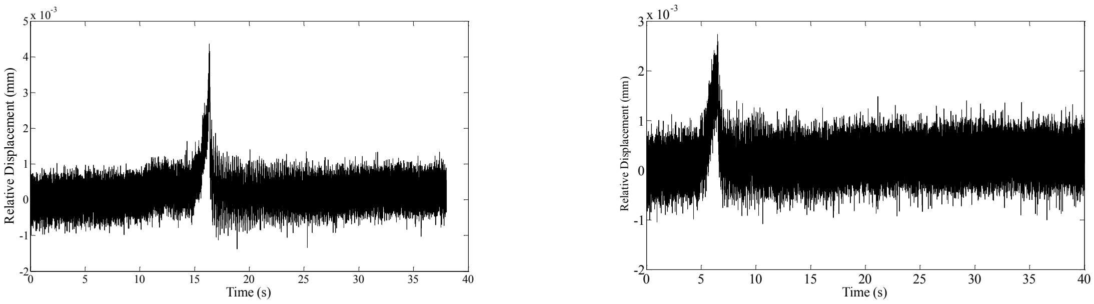
(d) S4

Figure 12 - Measured relative displacements when releasing shear connector SC1



(a) Releasing SC2

(b) Releasing SC4



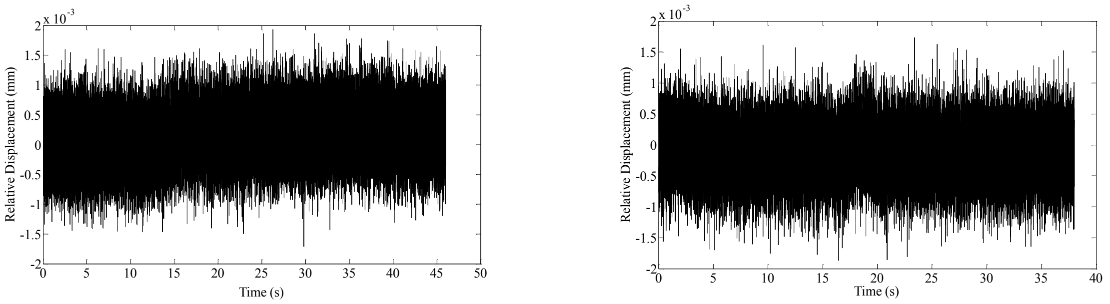
(c) Releasing SC6

(d) Releasing SC8

Figure 13 - Study on the sensitivity radius of a relative displacement sensor (S1)

(a) Releasing SC2

(b) Releasing SC4



(c) Releasing SC6

(d) Releasing SC8

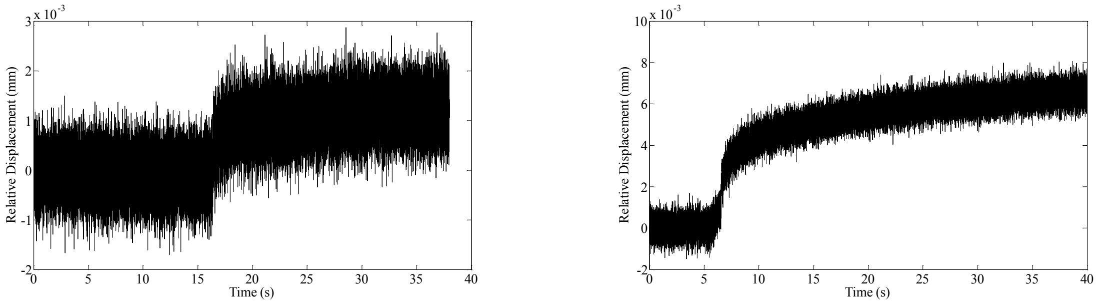
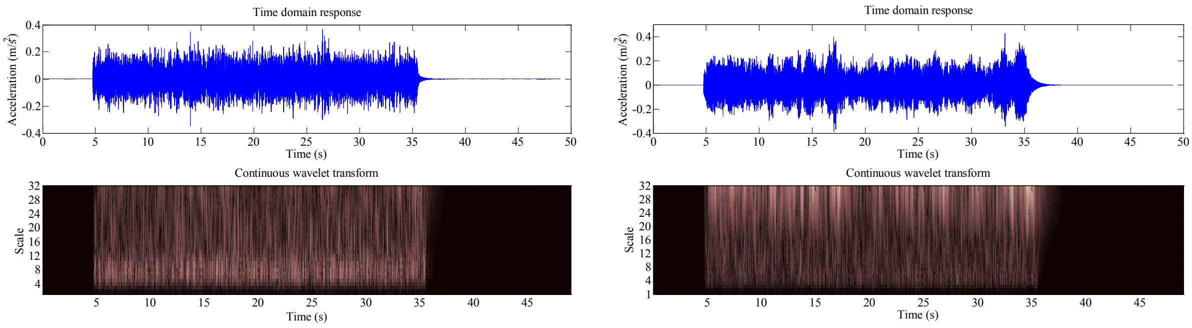


Figure 14 - Study on the sensitivity radius of a relative displacement sensor (S2)

Figure 15 - The bridge model with an exciter generating ambient vibrations

(a) A1 (b) A2



(c) A3 (d) A4

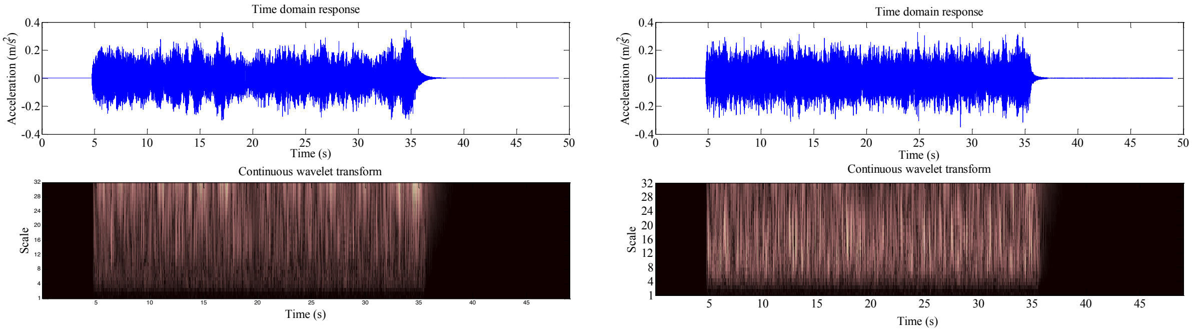


Figure 16 - Online health monitoring with accelerations under ambient vibrations

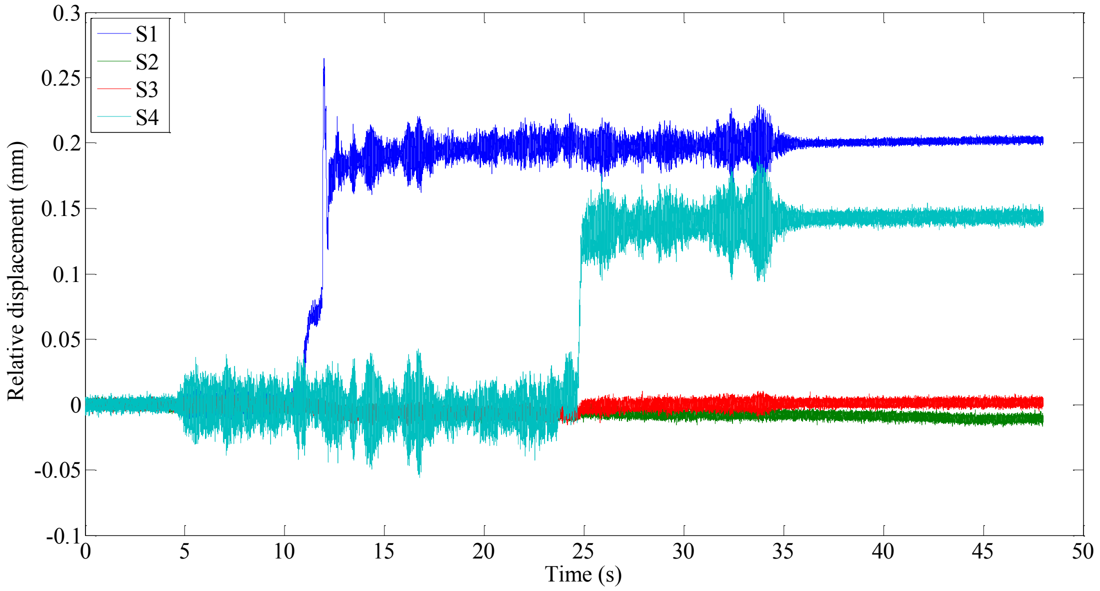


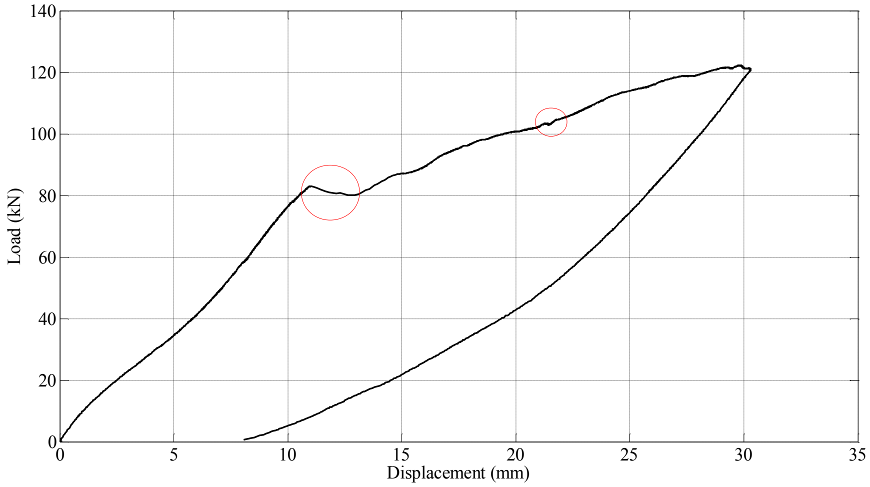
Figure 17 - Online health monitoring with relative displacements under ambient vibrations

(a) First loading

(b) Second loading

Figure 18- Experimental setup for composite bridge loading

(a) Displacement



(b) Relative displacement

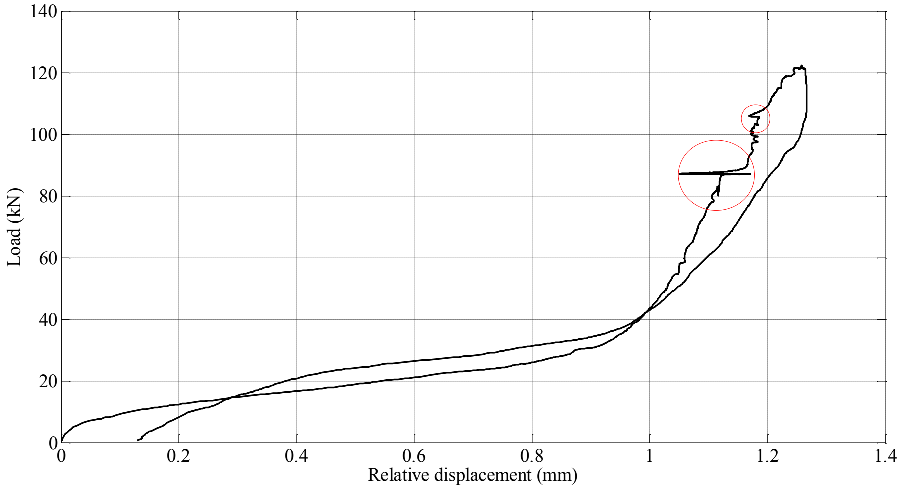


Figure 19 - Load-deformation curves in the first loading scenario (a) Load-vertical deflection curve for D2, (b) Load-relative displacement curve for S2

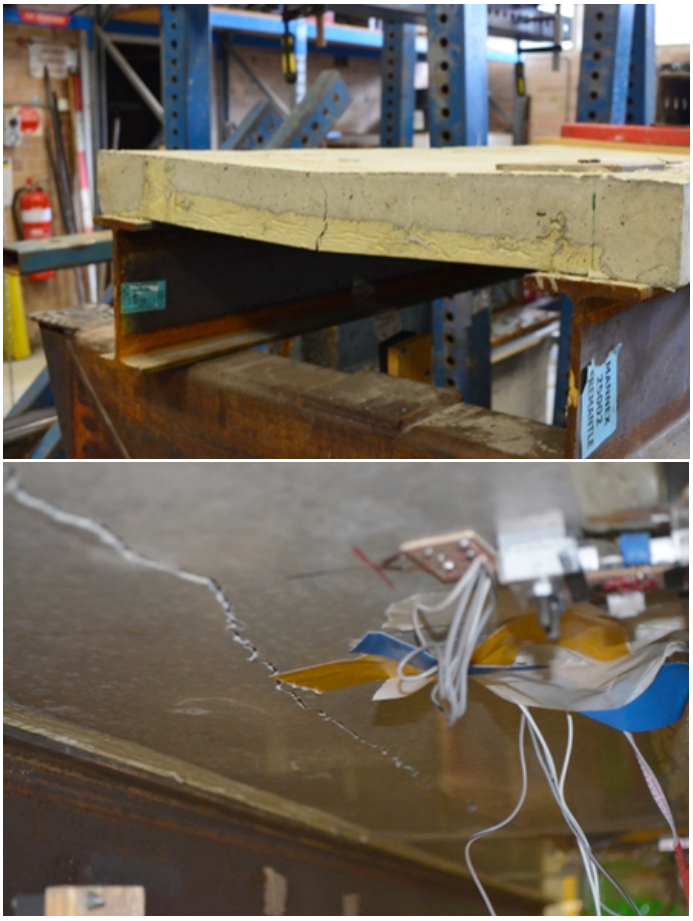
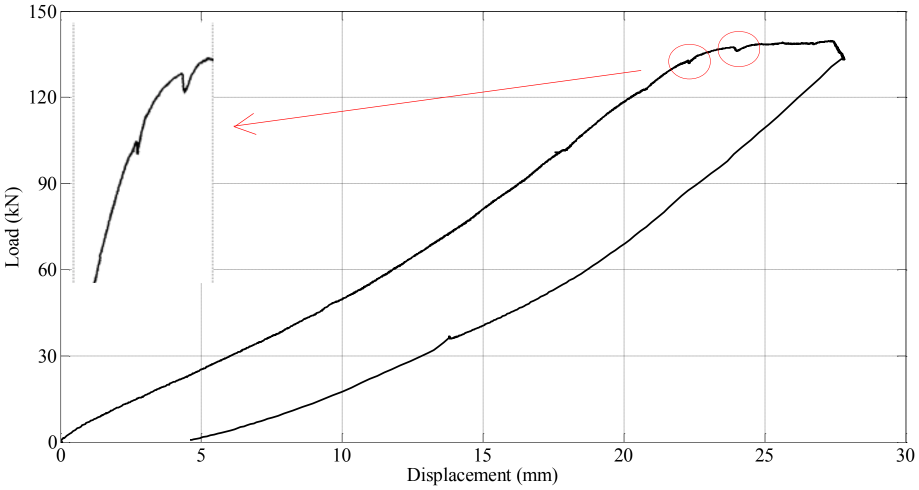


Figure 20 - Observed crack in the first loading scenario

(a) Displacement



(b) Relative displacement

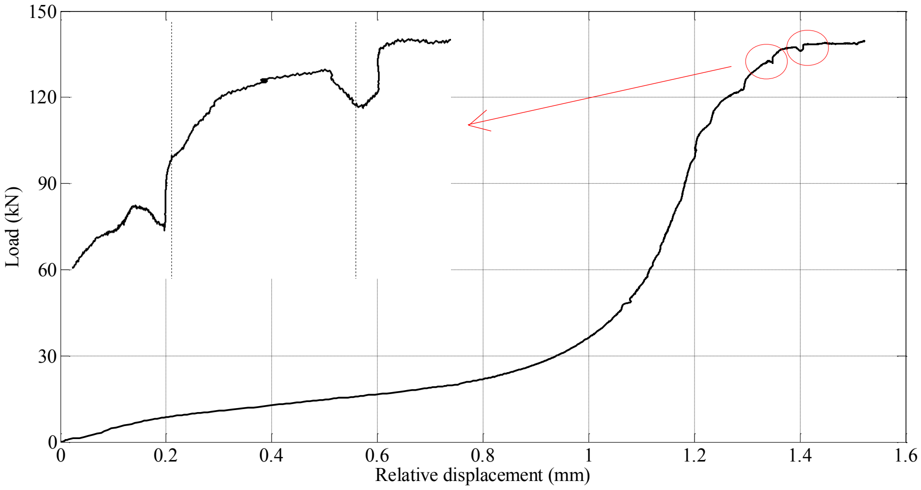


Figure 21 - Load-deformation curves in the second loading scenario (a) Load-vertical deflection curve for D2, (b) Load-relative displacement curve for S2

Figure 22 - Observed additional cracks in the second loading scenario