XII International Conference on Structural Dynamics IOP Publishing
Journal of Physics: Conference Series **2647** (2024) 192007 doi:10.1088/1742-6596/2647/19/192007

A Highly Stretchable Strain-based Sensing Sheet for the Integrated Structural Health Monitoring

Hui Zhang; Sherif Beskhyroun
Auckland University of Technology (AUT), Auckland, New Zealand.
E-mail: `hui.zhang@aut.ac.nz; sherif.Beskhyroun@aut.ac.nz`

Abstract. In this study, a flexible strain sensing system that can be applied to full-scale reinforced concrete frame structures is presented. In order to fulfil the criteria for strain detection that are posed by various structural components, the flexible strain gauge is offered in two distinct configurations: one full bridge and one double half bridge. A strain configuration selector is built on the basis of this information. The selector is designed to enable the system to flexibly switch strain modes for measuring axial or bending strain without adjusting the installation location of strain sensors. The first section of this study focuses mostly on elaborating on the methodology behind the development of a flexible strain system. This method was primarily designed with the aim of detecting the abnormalities in the strain field that are brought on by structural damage in order to accomplish the goal of local detection. The creation of a strain configuration selector also enables the conversion between two different strain measures whenever it is necessary without requiring the sensor installation to be moved to a new position, which helps to significantly reduce the amount of cost associated with sensor deployment. The performance of the flexible strain sensing system as well as its sensitivity were evaluated by doing the cyclic load testing on a full-scale RC frame. Both half-bridge and full-bridge strain gauges are installed in the critical components, such as beams and columns. In addition, 14 linear variable displacement transducers (LVDTS) were placed on the RC frame in order to monitor variations in displacement and deformation. The findings of the experiments indicate that the flexible strain sensor exhibits a high degree of sensitivity, and it is therefore suitable for integration into a structural health monitoring (SHM) system for the purpose of tracing the strain caused by localised structural damage. Additionally, it is able to monitor the strain trend on the complete scale of the frame model. In future work, the flexible strain system will be modified and enhanced by using wireless technology for data transmission in order to build a wirelessly integrated structural health monitoring (SHM) system.

1 Introduction

The capability of continuously monitoring the behaviour of structures is essential for maintaining the safety and durability of those structures. The term ”Structural Health Monitoring,” or SHM, refers to the process of using sensors and monitoring systems to identify any indications of damage, deterioration, or ageing in a structure that may have an impact on the structure’s ability to function safely and effectively. The present SHM techniques, however, usually rely on manual or visual inspections, which can be time-consuming and costly, and they may not be able to detect small-scale damage in some unreachable areas. This is a highly noteworthy issue in the case of civil structures, such as buildings, bridges, and pipelines, which are subjected to a variety of environmental and load conditions during the course of their lifetimes. Consequently, numerous academics have spent the last few decades optimising SHM systems [1, 2, 3, 4, 5].

Visual inspection is the approach of non-destructive evaluation (NDE) that is used most frequently. Nevertheless, this technique is unreliable, particularly when monitoring large structures and areas that are difficult to reach. Traditional visual inspection methods heavily rely on on-site inspectors, which makes them prone to human error and unable to provide an accurate assessment of the structure's condition. The SHM system is able to deliver a more accurate assessment and lower the probability of an unsuccessful evaluation thanks to the assistance of high-resolution sensors. Long-term monitoring data in real time also helps to predict the performance of structures and the maintenance needs of such structures, which helps to maximise structural integrity and safety while also prolonging the lifespan of the structures [6].

In order to overcome the NDE limitations, there has been an increased amount of interest in the development of strain-based sensing systems for integrated SHM [7, 8, 9]. These sensors can be attached to the surfaces of structures, allowing for real-time monitoring of the behaviour of the structures as well as the detection of even minute shifts in tension that may indicate damage. It is possible to eliminate the need for visual inspections and increase the accuracy of local damage detection by using a strain-based sensing system.

This research paper presents a strain-based sensing sheet that has been developed for the integrated SHM system. A strain configuration selector is intended to allow for flexible switching between axial and bending strain measurement without changing the sensor location. The flexible strain sheet is available in two separate configurations: one full bridge and one dual half bridge. The approach that goes into the development of the flexible strain system is centred on the detection of irregularities in the strain field that are caused by structural damage, which ultimately leads to the diagnosis of local damage. During cyclic load testing performed on a full-scale RC frame, the performance and sensitivity of the flexible strain sensing system were evaluated. Both half-bridge and full-bridge flexible strain sheets were installed in critical components such as beams and columns, and 14 linear variable displacement transducers were used to monitor displacement and deformation of the entire RC frame. According to the results, the flexible strain sensor offers a high degree of sensitivity and is an excellent fit for integration into a structural health monitoring system. In future work, the strain-based flexible sensor system will be further developed as part of the ongoing development process of the SHM system. To build an integrated SHM system, wireless technology will be added to the flexible strain system as part of the upgrade. This will enable it to monitor data and wireless transmission in real time for the development of integrated SHM systems.

2 Strain-based Sensing Technology

In this chapter, the design concept of a strain sensor system is broken down and discussed. In the beginning, a basic explanation of the Wheatstone bridge configuration of the resistance strain sensor is given. Following this, a description of the layered structure of the fabricated materials is presented. Finally, the design of the strain configuration selector is presented.

2.1 Strain Gauge Principle and overview

In the 1920s, strain-based sensors first began to be used in the field of SHM, which is essentially divided into two categories: discrete electrical sensors for the monitoring of local damage and distributed sensors for the monitoring of structural integrity. The implementation of high-sensitivity modal parameters is the most important factor in achieving accurate local damage identification. In recent years, strain-based sensing techniques have become a significant area of research due to their high level of sensitivity.

The technology of the strain sheet is utilised extensively in a wide range of applications, including the monitoring of the structural health of a building, load testing, and force sensing. For the purpose of structural health monitoring, for instance, strain sheets can be glued to a structure in order to monitor the behaviour of the structure while it is being loaded. This can provide important information regarding the structure's condition and assist in preventing potential damages.

There are many various strain sheets available, such as uniaxial, biaxial, and multi-axial strain sheets. Each type of strain gauge, whether uniaxial, biaxial, or multiaxial, faces the same limitation: a single strain gauge put on the structure can detect strain in only one direction at a time. If strain measurements need to be taken in more than one direction at the same time, then new strain sensors will need to be installed and placed in each of the directions being measured. In response to this challenge, the full-bridge sensor that was designed for this study is able to switch freely in bending and axial strain without the need for the installation of a new sensor or the adjustment of the measurement direction of the existing sensor. The specific design principles and details will be introduced in the next section.

2.2 Strain sensing principle

In most cases, a strain sensor will have a layout that includes a quarter bridge, a half bridge, and a full bridge. In this study, two configurations—full bridge and half bridge—are applied to various structural elements. Because the majority of strain sensors are extremely sensitive to temperature in natural environments, it is essential that these sensors be capable of compensating for variations in temperature. In this regard, the whole bridge circuit of the Wheatstone bridge is a very reliable technique for achieving the goal of temperature compensation. The configurations of a half-bridge and a full-bridge are used in this study, as previously stated; however, the half-bridge is also connected to the full-bridge via the strain configuration selector, which helps to ensure that the temperature compensation function works very well. A detailed design overview of the strain configuration selector is described in section 2.2. The resistance of a metal sheet will change depending on the amount of strain that is applied to it, and this is the fundamental idea underlying strain sheet technology. When a sheet of metal is stretched, its dimensions shift, which in turn causes the material's resistance to alter as well. Because the amount of strain is proportional to the size of the change in resistance, it is easy to determine the amount of strain by measuring the amount of change in resistance. Figure 1 illustrates that the full-bridge strain gauge has four resistance units inside its construction (R1, R2, R3, and R4). In this specific study, a consistent excitation voltage of 3.3 v is transmitted between the two electrodes designated as Vex+ and Vex-. The ratio relationship between the measured output voltage Vout and the excitation voltage (input) Vin can be determined by using the equation (1)

$$Vr = \frac{Vout}{Vin} = \frac{R4}{R4 + R3} - \frac{R3}{R3 + R2} \tag{1}$$

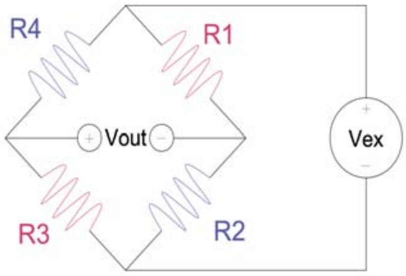


Figure 1: A typical whetstone bridge circuit

As can be seen from the above equation, when there is no strain being applied, the bridge will be in a state of equilibrium, during which all of the resistance values will be equal to one another, and the output of the bridge will be zero. Because every resistor is manufactured from the same material, they all have the same value for the thermal resistance coefficient. In other words, the change in resistance does not change regardless of the temperature. Because of this, while the bridge is in a state of equilibrium, the output voltage Vout can remain the same. This is the theory that underlies the fact that the full bridge configuration of the strain gauge can achieve temperature compensation. In addition to this, the resistance of the strain gauge is made up of wire, the sensitivity of the strain can be represented in terms of the gauge factor (GF):

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon} \tag{2}$$

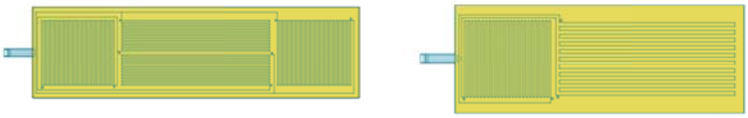
Where R is the value of the wire's initial resistance, L is the length of the wire when it is first measured, ΔR and ΔL reflects the changing resistance value and length and ϵ indicates the mechanical strain.

2.3 Flexible Strain Sheet Prototype

Strain gauges that come in a variety of configurations can be utilised in a wide range of real-world applications, among which the sensitivity of strain gauges that come in a half-bridge or full-bridge configuration is the highest. In natural environmental conditions, it is important to consider how to mitigate the negative impact that changes in temperature possess. However, the full bridge configurations that are currently on the market are single strain gauges, so it is not possible to install complementary strain gauges on opposite sides of the test specimen. This research resulted in the development of a flexible strain sensor that makes use of two distinct full-bridge configurations, which National Instruments [10] refers to as Configuration Type II and Configuration Type III, respectively. A flexible strain gauge is designed for half-bridge structures in order to measure the strain that key components of the structure are subjected to. In addition, a strain configuration selector is developed in order to connect two half-bridge strain gauges in order to form a full-bridge configuration. Both of these developments are carried out in order to measure the strain that key components of the structure are subjected to. In the following section, a comprehensive description of the strain configuration selector will be provided.

Although the four resistance elements that make up a conventional strain gauge are typically the same size, in actual use, these gauges do not perform very well when measuring the strain in slender members. Within the scope of this study, a half-bridge and a full-bridge configuration are both implemented. While the full-bridge configuration can be directly installed in the span of the beam, the half-bridge configuration can be installed on the opposite side of the member in order to measure the strain near the bottom of the column. In contrast, the half-bridge configuration can be flexibley installed on any opposite side of the member in order to measure the strain near the top of the beam. In addition, the frame of the proposed design is a long rectangle, which ensures both the sensitivity and temperature compensation performance of the device while simultaneously covering as much surface as is feasible. Its size is four to five times larger than the sensors that are currently available on the market, and it can be attached to the majority of members that are slender. Figure 2 provides an illustration of the particular design prototype.

The full-bridge configuration has four sensing elements, while the half-bridge configuration only has two sensing elements. The layers of both configurations are primarily made up of three types of materials: a 25 μm polyimide (PI) substract layer, a 20μm Constantan conductive layer, and a 25μm glue layer for bonding the layers together 3. Polyimide is widely implemented in



(a) (b)

Figure 2: Design of the strain sensing sheet: (a) Full-bridge configuration (b) half-bridge configuration.

the aerospace, chemical, and environmental industries due to its ultra-high resistance to high temperatures, outstanding mechanical characteristics, and resistance to chemical corrode. The fibres that are used to make PI materials are some of the strongest fibres available in terms of modulus, strength, density, elongation at break, and temperature resistance [11]. This is the characteristic of PI materials that stands out the most. A high degree of stretchability is essential for flexible strain gauges to function properly. The conventional strain gauges that are most commonly used on the market today not only have a small sensing area, but also the compressive and tensile strength of the material itself is not adequate for long-term structural damage detection. Because of its high temperature resistance, resistance to corrosion, and high stretchability, polyimide (PI) is the primary material for flexible strain gauges in this investigation. This is because of the possibility that PI can provide more opportunities for the practical application of strain sensors in structural health monitoring.

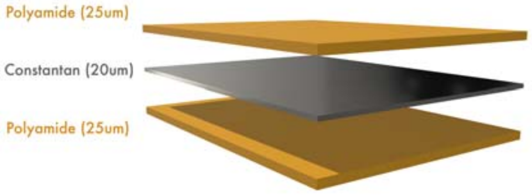


Figure 3: Components of the strain sensin sheet

3 Developemnt of Strain Sensor Configuration Selector for bi-axial Strain Measurement

3.1 Full-bridge Type II and Type III

The full-bridge type II only measures the bending strain, and Figure 4 illustrates the direction in which it should be installed on the sample that is being measured. There are a total of four active strain elements, two of which (R3 and R4) are installed in the direction of the bending strain. These active strain elements are positioned as follows: one at the top of the specimen and one at the bottom that corresponds to it. The other two strain elements, R1 and R2, function as Poisson gauges and are mounted laterally (vertically) on both sides of the sample, the output readings of this type can be converted to strain by equation (3).

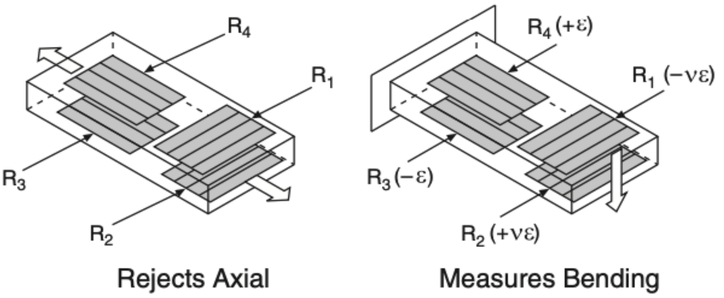


Figure 4: Full-Bridge Type II Rejecting Axial and Measuring Bending Strain [10]

$$strain\,(\varepsilon) = \frac{-2Vr}{GF\,(1+v)} \tag{3}$$

The full-bridge type III measures only the axial strain. The axial direction of the strain gauge mounting specimen is shown in figure 5. There are a total of four active strain elements, two of which are installed in the direction of axial strain (R2 and R4), one of which is installed at the top of the specimen, and the other of which is installed at the bottom corresponding to the top. Poisson gauges consist of two additional strain elements that are mounted transverse (perpendicularly) on either side of the sample. These strain elements are denoted by R1 and R3, respectively. The strain values for this type of installation can be converted from equation (4).

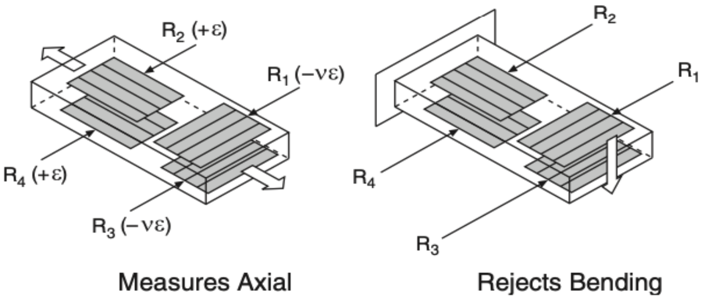
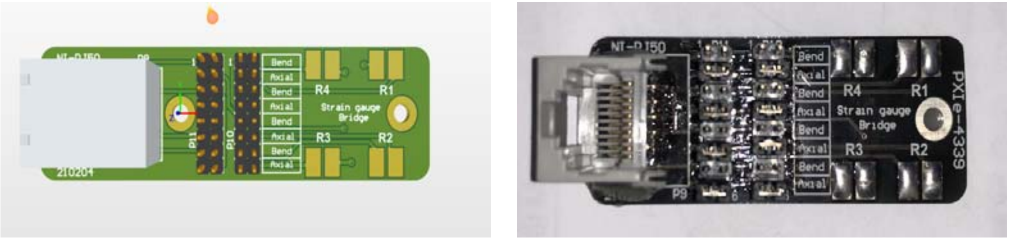


Figure 5: Full-Bridge Type III Measuring Axial and Rejecting Bending Strain [10]

$$strain\,(\varepsilon) = \frac{-2Vr}{GF[(v+1) - Vr\,(v-1)]} \tag{4}$$

The vast majority of strain gauges that are currently in use are only able to measure strain in a single direction (either bending or axial), which corresponds to the Type II and Type III gauges described earlier. In real-world applications, the strain gauge has to be glued to the surface of the measuring specimen before it can be read. Because the position cannot be changed once it has been installed, strain can only be measured in a single direction. As a solution to this challenge, this study developed a strain configuration selector, which is illustrated in Figure 8. The configuration selector allows for unrestricted switching between axial strain and bending strain measurements, all without requiring the installation position of the strain sensor to be adjusted. At the left end of the selector is an RJ50 port that serves as a connection point for wired transmission to the data acquisition. In the middle is a switch key component that enables the measurement of bending as well as axial strain, and jumpers can be used to quickly connect or switch between the two different modes. The solder interfaces (R1, R2, R3, and R4) are used for welding the strain sensors.



(a) (b)

Figure 6: Design of the strain sensor configuration selector (a) 3D view of the design (b) prototype image.

4 Experimental test

4.1 Test structure setup and procedures

This investigation will evaluate the full-scale size of a precast reinforced concrete frame structure (with beams that are 2950 mm long and columns that are 2650 mm high) (Figure 7). The compressive strength of the concrete that was used for the frame structure was 25 MPa, and the frame beam section was rectangular with dimensions of 230mm*220mm. In the vicinity of the beam-column joint, a full bridge sensor has been attached. Near the bottom of the right column, there are two half-bridge sensors that have been installed on both sides of the column, and connected by the strain gauge configuration selector(Figure 8). In addition, in order to provide a higher level of precision and a multidimensional reference for the experiment, there were 14 linear variable differential transformers (LVDT) that were installed. And furthermore, the right end of the beam was fitted with a draw-wire displacement sensor, which acts as the baseline of lateral displacement brought on by the load that was applied to the frame. Figure 9 demonstrates the location of the sensors' installation along with the frame setup. In order to apply a horizontally reverse load to the frame structure during the experiment, an MTS hydraulic actuator was utilised. Hydraulic actuators are capable of applying loads of up to 1000 kN and having a static stroke of up to 500 m. The cyclic loads are gradually applied to the transverse frame beams by the hydraulic actuator as it moves. In each loading step, LVDTs were employed to examine the vertical displacement of the beam in addition to the transverse displacement of the column. To sum up, in order to determine the strain value on the concrete surface of the beam and column, respectively, strain sensing sheets are implemented as the measurement device for collecting the strain value and monitoring the structural member performance.

As shown in Table1, in the experiment, the reinforced concrete frame was gradually loaded from an initial drift of 0.25% (5.3mm) to a drift of 1.25% (26.3mm) in 0.25% increments with each test.

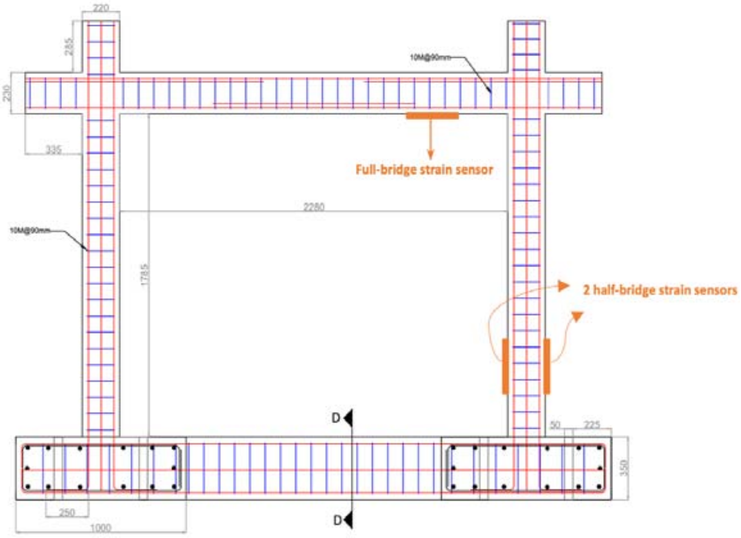
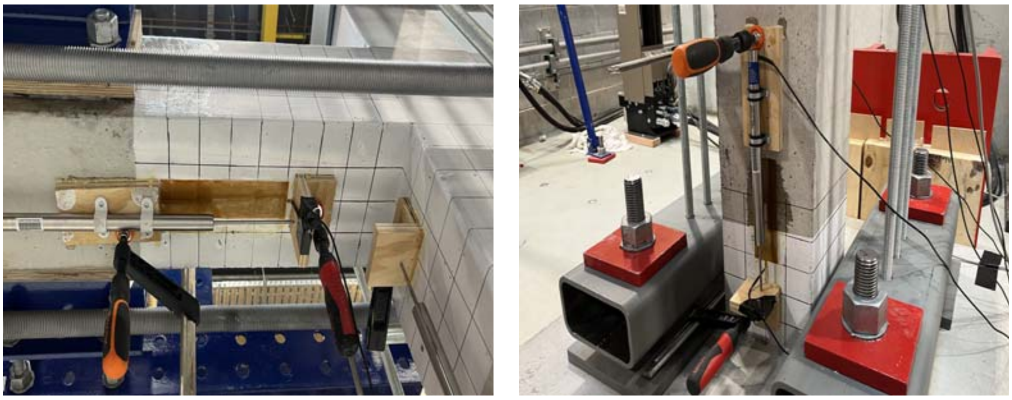


Figure 7: Front view of the RC frame and steel reinforcement

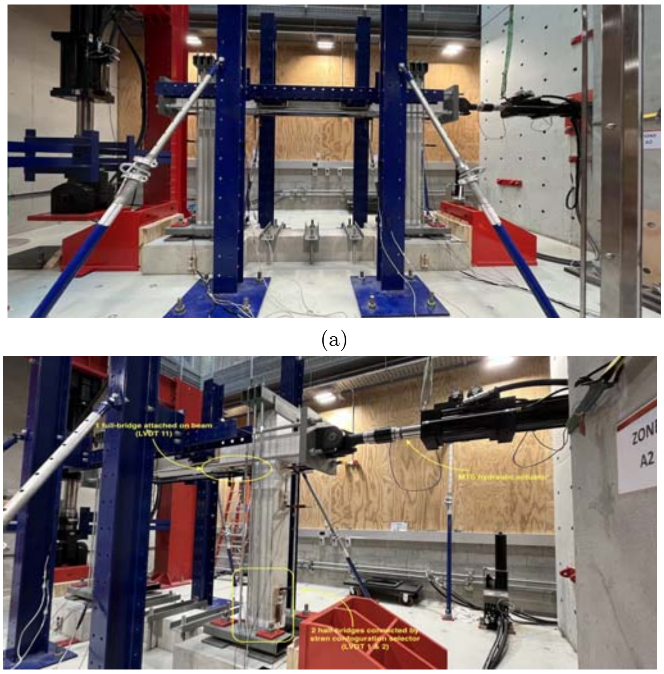


(a) (b)

Figure 8: Flexible strain sensors installation (a) 1 full-bridge installed on beam with LVDT 11 (b) 2 half-bridges connected as 1 full-bridge installed on column with LVDT 1 and 2.

Table 1: Cyclic Test Procedure

Test Cycle	Drift (%)	Max Load (kN)
Test 1	0.25 (5.3mm)	75
Test 2	0.50 (10.5mm)	95
Test 3	0.75 (15.8mm)	125
Test 4	1.00 (21.0mm)	140
Test 5	1.25 (26.3mm)	168



(a)

(b)

Figure 9: Frame setup of the experimental test (a)Front view of the experimental test setup (b) Frame side view and flexible strain sensors setup.

4.2 Test Result

The purpose of this experiment is to test the performance of a flexible strain sensor that has been developed. The sensor will be installed on a full-size reinforced concrete frame structure and will be put through horizontal reciprocating load testing. During the course of the experiment, a number of measuring devices, such as linear variable differential thermometers (LVDT), wire-drawing displacement sensors, and strain sensors, were utilised in order to collect performance data pertaining to structural members.

The increasing drift of the entire frame after the load has been applied in the experiment is what ultimately produces the response of the entire structure. The specimen was nearly symmetric in the horizontal direction of push and pull, and the maximum horizontal force that it resisted was 161 kN and 145 kN, respectively, as can be seen from the RC Frame horizontal load-displacement cyclic response curve that is shown in Fig 10. Although the results demonstrate distinct peaks in each direction, the shape of the hysteretic response curves remains almost identical throughout the frame, and the same scenario applies to the gradual decrease of loads between each test period. The relationship that exists between yield strength and the loads on beams and columns, as well as the strain in the concrete, is depicted in Fig 11. Furthermore, the relationship between yield strength and beam and column loads as well as concrete strain is depicted. According to the findings, the degree to which beam and column loads are increased leads to a corresponding rise in the amount of internal strain that concrete experiences. The strain sensor has the capability of providing an accurate measurement of the performance of the structural component by accurately capturing the strain value of the concrete surface of the beam and column, respectively.

The sensing devices that were developed in the research carried out exceptionally well in their

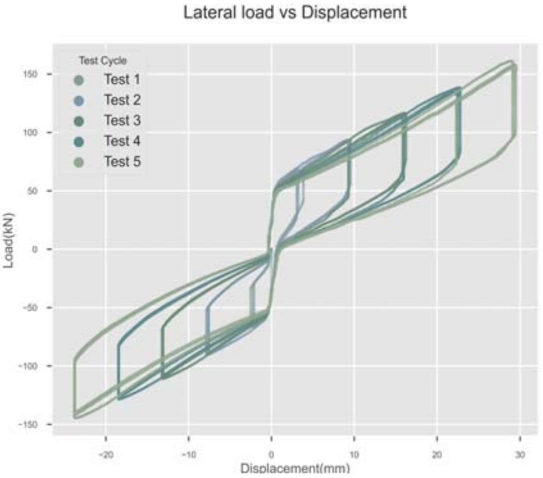
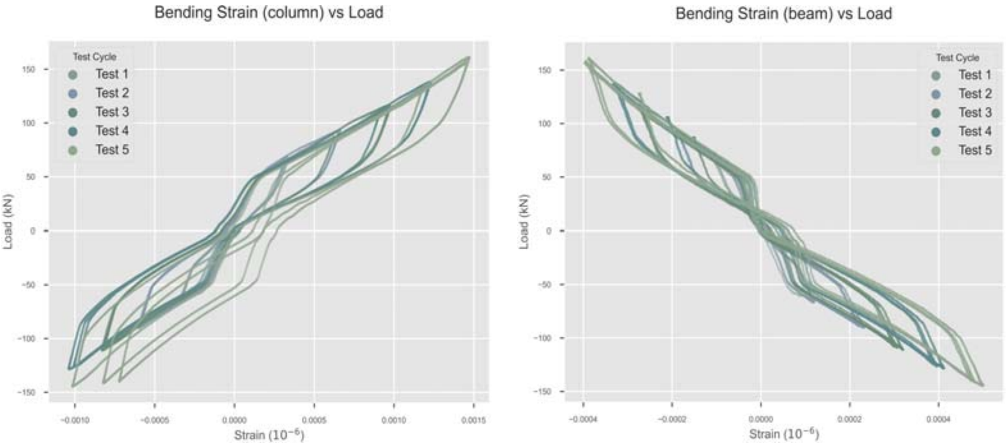


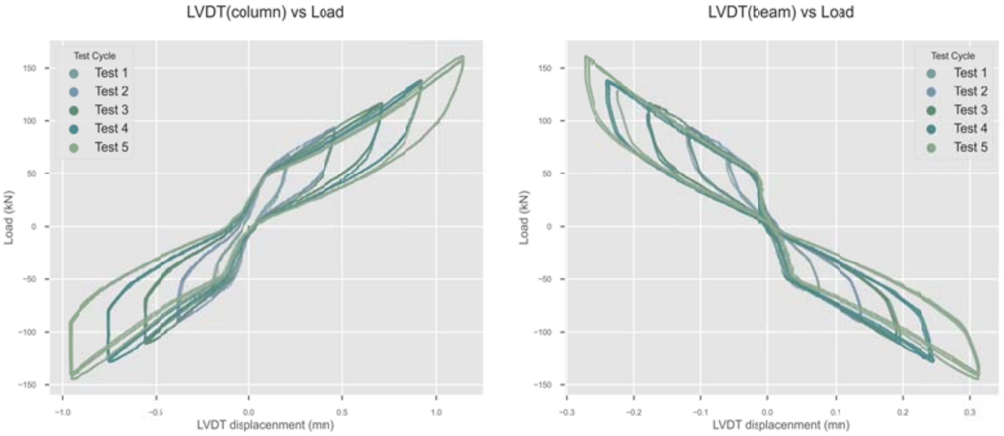
Figure 10: Load vs displacement response curves of the RC Frame

respective tests. This demonstrates that the developed flexible strain sensor is highly stretchable and sensitive enough to capture the strain of full-size RC frame structural components even when the structure is subjected to a high cyclic load (the maximum drift is 1.25%-26.3mm and the load is up to 168KN). In addition, the application of strain sensors in this investigation exemplifies the outstanding functionality of this category of measuring instrument. The sensor is able to measure strain in a continuous manner throughout the cyclic loading process, thereby providing data in real time that can be used to monitor the performance of structural components. In addition to being simple to install, flexible strain sensing sheets do not need any specialised hardware, which makes them an economical solution for monitoring the structural health of a building and identifying localised damage.



(a) (b)

Figure 11: Strain vs Load diagram (a) Strain sensing sheets on the column(2 half-bridges) (b) Strain sensing sheet on the beam (1 full-bridge).



(a) (b)

Figure 12: LVDT vs Load diagram (a)LVDTs on the column (b)LVDTs on the beam.

5 Conclusion

Overall, this highly malleable and flexible strain device provides accurate measurements of concrete strain. Strain is an important parameter for understanding the behaviour of structural members and monitoring damage. The flexibility and adaptability of the developed strain sensor in this study makes it a valuable tool for real-time monitoring of structural component performance. Because of its precision and sensitivity, the flexible sensor system enables real-time monitoring of the performance of structural components as well as the detection of localised damage. The application of flexible sensing sheets is not only simple but also economical, which makes them an attractive option for the purpose of structural health monitoring and the detection of local damage. This study demonstrates the effectiveness of the developed biaxial flexible strain sensors for capturing the strain of concrete members under cyclic loads and highlights their potential for use in structural monitoring of performance in other types of concrete structures. Additionally, this study demonstrates the effectiveness of the developed biaxial flexible strain sensors for capturing the strain of concrete members under static loads. The flexible strain gauge will continue to be developed as part of future research, and it will be fully equipped with wireless transmission technology to enable an integrated real-time structural health monitoring system.

References

[1] An H, Youn B D and Kim H S 2022 *Composite Structures* **279** 114863
[2] Corbally R and Malekjafarian A 2022 *Engineering Structures* **253** 113783
[3] Gordan M, Sabbagh-Yazdi S R, Ismail Z, Ghaedi K, Carroll P, McCrum D and Samali B 2022 *Measurement* 110939
[4] He Y, Zhang L, Chen Z and Li C Y 2022 *Engineering with Computers* 1–19
[5] Lin M, Guo S, He S, Li W and Yang D 2022 *Composite Structures* **286** 115305
[6] Hsieh K H, Halling M W and Barr P J 2006 *Journal of Bridge Engineering* **11** 707–715
[7] Rainieri C, Fabbrocino G and Cosenza E 2011 *Mechanical Systems and Signal Processing* **25** 3010–3026
[8] Ozer E and Feng M Q 2020 *Start-up creation* (Elsevier) pp 345–367
[9] Wan H P and Ni Y Q 2018 *Journal of Structural Engineering* **144** 04018130
[10] National Instruments Measuring strain with strain gages URL `https://www.ni.com/en-nz/shop/data-acquisition/sensor-fund`
[11] Maurya A K, Kumar S, Singh M and Manik G 2022 *Materials Today: Proceedings*