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Optimum Placement of Long Gauge FBG Sensor in Reinforced Concrete Bridge: *A Case Study*

Sayantani Lala[1,2,5], Nandini Basumallick[1,3], Palas Biswas[1,3], and Somnath Bandyopadhyay[1,4]
[1]Fibre Optics & Photonics Division, CSIR-Central Glass & Ceramics Research Institute (CGCRI), Kolkata, India

E-mail: sayantani@cgcri.res.in

Abstract. In the world today, civil infrastructure plays a major role in the advancement of the modern age. They are huge in scale, complex in their behaviour and create great impact in everyday life. To ensure safety of these structures, assessment of their structural integrity is an important and challenging task. The sole purpose of structural health monitoring is to detect damage in the structures and suggest suitable rehabilitation measures. Various sensors are employed to achieve the task of damage detection and establish a warning system to avoid failure of the structures. For large structures, long-gauge Fibre Bragg Grating (FBG) sensors which are sensitive to the global behaviour, can be suitably used for this purpose. However, health monitoring of a structure with large number of sensors is expensive and hence there is a need to optimize the number of sensors deployed to minimize the cost of the exercise without compromising on performance assessment. For this purpose, several optimization algorithms are available in literature. In this study, the Effective Independence Method (EIM) which optimizes the response of the structure based on modal analysis, is used to derive the Optimum sensor placement (OSP) protocol for a reinforced concrete (RC) bridge-deck in Poland, the geometry of which has been taken from literature. This will enable the placement of 40 long gauge FBG sensors in regions for efficient damage response in the bridge-deck. Further, the optimum orientation of the sensors is further validated with a finite element model of the bridge-deck, where a moving load is applied, and strains are recorded in the sensing fibre in both longitudinal (along length) and transverse (along breadth) alignments. It has been found that long gauge FBG sensors placed in the transverse direction are more efficient in damage detection than when they are placed longitudinally.

1. Introduction

The long-gauge deformation sensor, by definition, is a sensor whose gauge-length is longer than the maximum distance between discontinuities [1]. The measurement obtained with this sensor is based on the average strain between the end supports of the sensor. These type of sensors are more suitable for large concrete structures which have several local defects like cracks, air pockets etc. Hence instead of point sensors, which are more sensitive to local defects, long gauge sensors which are more sensitive

[2] Scientist
[3] Principal Scientist
[4] Chief Scientist
[5] To whom any correspondence should be addressed.

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to average strain, indicative of overall structural behaviour, is desirable. In long-gauge Fibre Bragg Grating (FBG) sensor, the fused silica fibre, which acts as the sensing element is installed between two anchors separated by gauge-length in a suitable package. The anchors are rigidly attached to the structure and any change in the original structure will generate strain in the connecting fibre. The advantage of using FBG sensor is that it is inert to environmental parameters and harsh conditions, has long-term stability, does not interfere with electromagnetic signals, can be multiplexed and can be compactly packaged for application in any structure. However, in addition to the type of sensor, the placement of the sensor is also an important parameter for efficient damage detection in a structure.

2. Background of the study

The performance of the structures can be monitored effectively with sensors. However, when the structure is large, the sensors needs to be placed at correct locations, in order to capture the behaviour of the entire structure. Also, an optimal number of sensor is to be employed in order to strike balance on the cost and efficiency of the health monitoring. By definition, an optimal sensor placement (OSP) is defined as a sensor configuration that achieves the minimum cost while observing pre-specified performance criteria [2]. The OSP has a potential to reduce life cycle costs of the structure considerably by reducing the cost of instrumentation of the structure with optimized number of sensors. It also improves the performance of the structural health monitoring (SHM) system, thereby reducing the risks of false– positive detection; as a result of which unnecessary closure and maintenance costs incurred due to false-negative detections can be avoided [3].

Literature study revealed that there are various OSP algorithms which can be employed in structures. The simplest method is the intuitive random search, which can be used when the structure is simple and small. But when the structure is large and complex, other heuristic search methods and genetic algorithms are used for optimization of sensors [4]. In this study, Effective Independence Method (EIM) is used as the optimization algorithm for deriving the OSP of long gauge FBG sensors for a reinforced concrete (RC) bridge in Poland.

3. Procedure

The case study here is based on an existing bridge structure in Poland [5] of length 40 m, width 11.25 m, and depth of 250 mm, with 3-lanes. Each lane is supported with steel girder along length and piers of height 2.95 m along the breadth. The schematic diagram of the structure is shown in figure 1.
A finite element model of the structure is built as shown in figure 2. The model is composed of are solid, homogenous elements. The grade of concrete is M25. The material properties are taken as prescribed in IS456:2000 [6]. The structure is discretized into a mesh size of 1m x 1m. A modal analysis is conducted on the structure to extract the first 30 mode shapes (N). The first five mode shapes are shown in table 1.
The OSP protocol of Effective Independence Method (EIM) [7] is applied to the structure to determine the optimum sensor locations. The idea of the EIM is to rank each degree of freedom based on its contribution to the linear independence of the target modality (Fisher Information Matrix). The degrees of freedom with lesser contribution degree are then deleted and the degrees of freedom with greater contribution are retained [8]. Thereby, the optimal sensor placement is realized. The algorithm of the EIM is shown in figure 3.
In the finite element model of the bridge-deck, the total number of nodes (n) is 429. Considering each node has three degrees of freedom (DOF), the total number of DOF is 1287. The shape of the modal matrix is shown in figure 4. The total number of sensors (m) to be placed is 40.

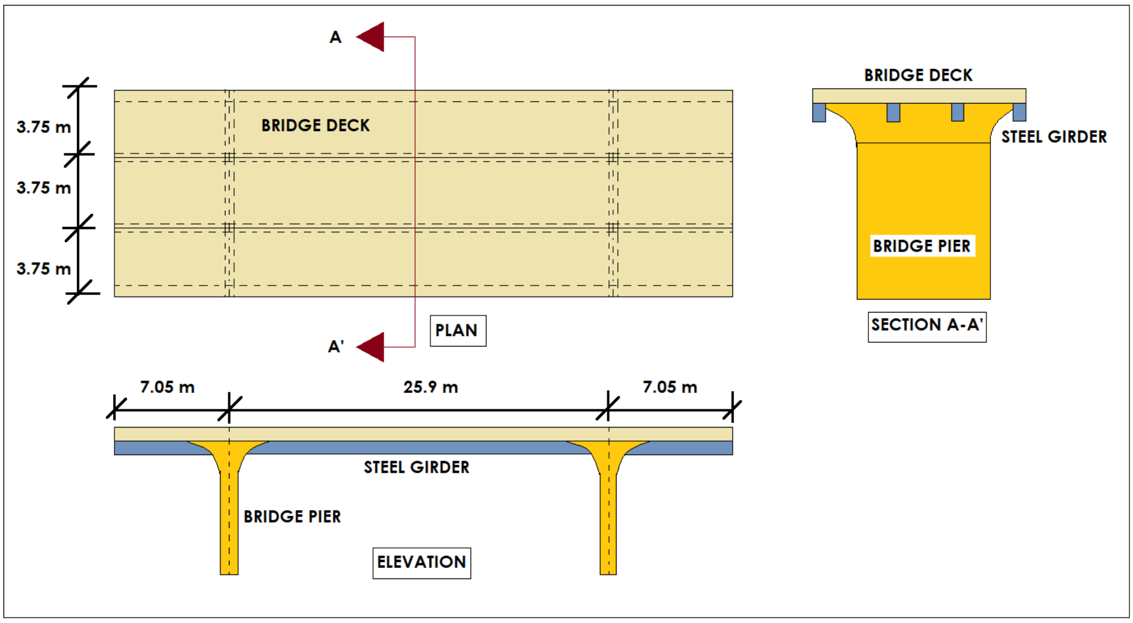


Figure 1. Schematic diagram of the Case study

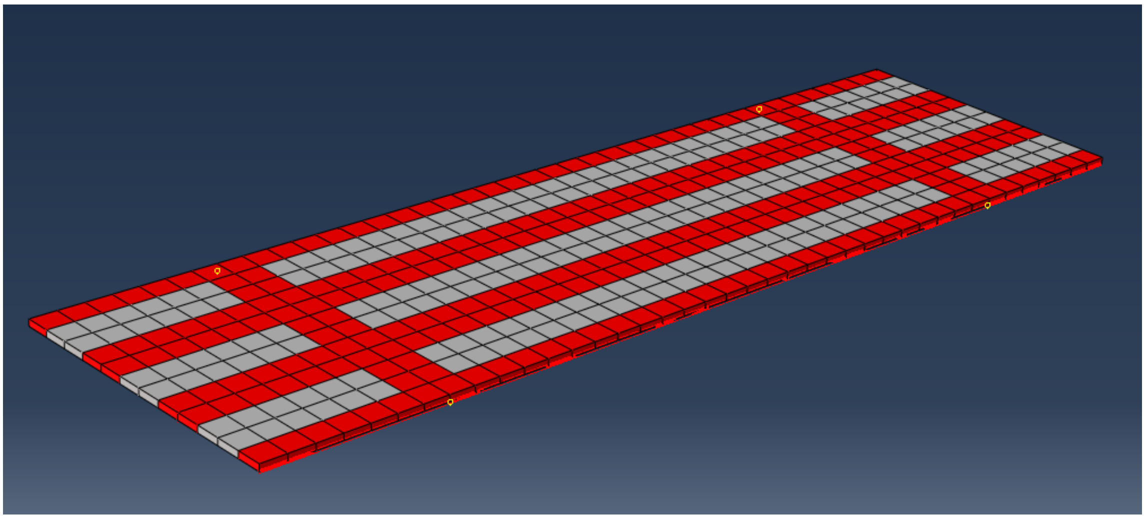
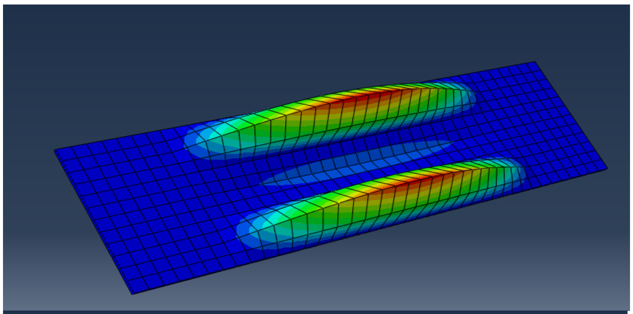
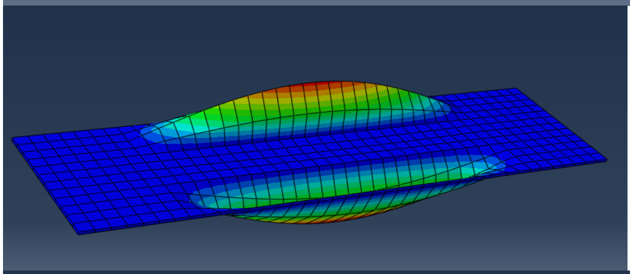
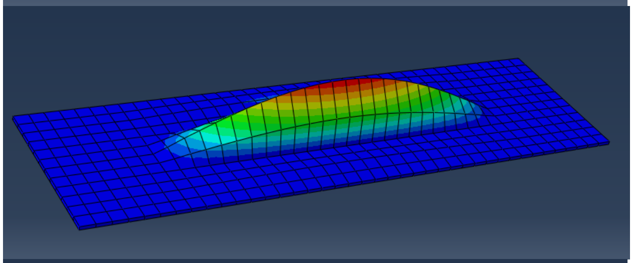
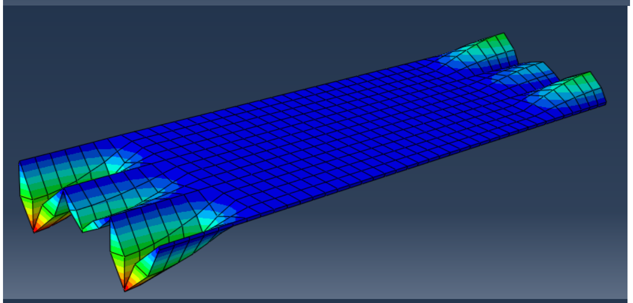
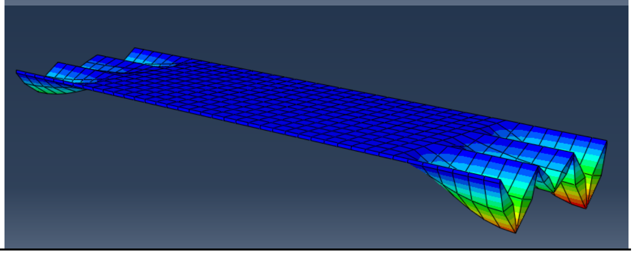


Figure 2. Finite element model of the bridge structure

Table 1. Modal frequencies of the bridge structure

Mode Number	**Natural frequency (Hz)**	**Mode Shape**

1	9.6765	
2	9.6778	
3	9.6802	
4	13.84	
5	13.841	

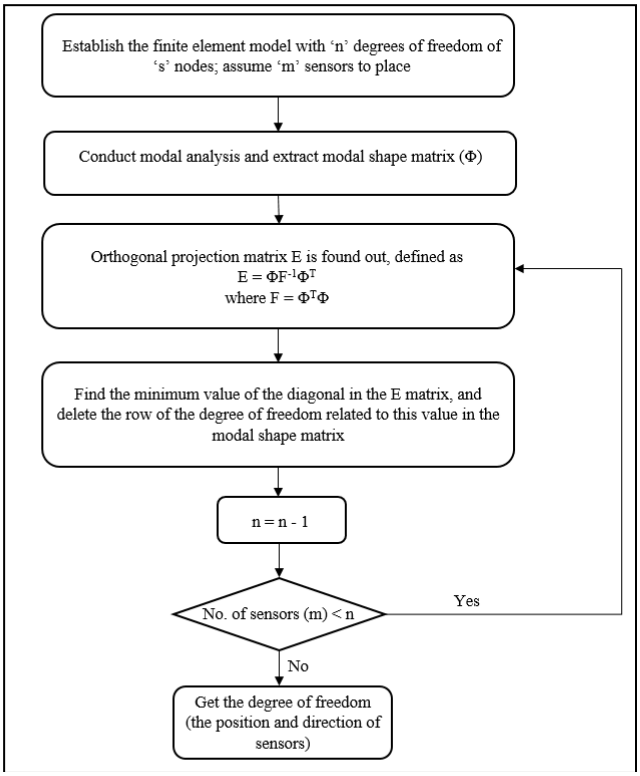


Figure 3. EIM Algorithm

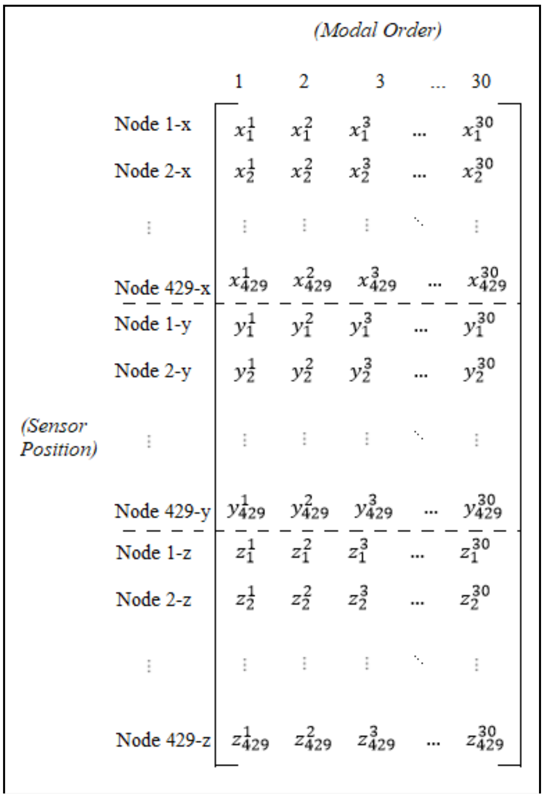


Figure 4. Modal matrix of the FE model

4. Validation model

In addition to the sensor location, the OSP also calculates the orientation of the sensor. Hence in order to validate the orientation obtained from the OSP, a simple long gauge FBG sensor (figure 5) is modelled as attached to the underside of the bridge deck and subjected to a moving load of 100 kN. Two cases are simulated as shown in figure 6. In the first one, the fibre in the long gauge FBG sensor is aligned along the length of the bridge and in the second case, it is aligned along the breadth of the bridge, modelled directly under the path of the moving load. As the bridge geometry is symmetrical, only half of the bridge is modelled to reduce computational costs. The strain in both these cases are compared under the same loading condition.

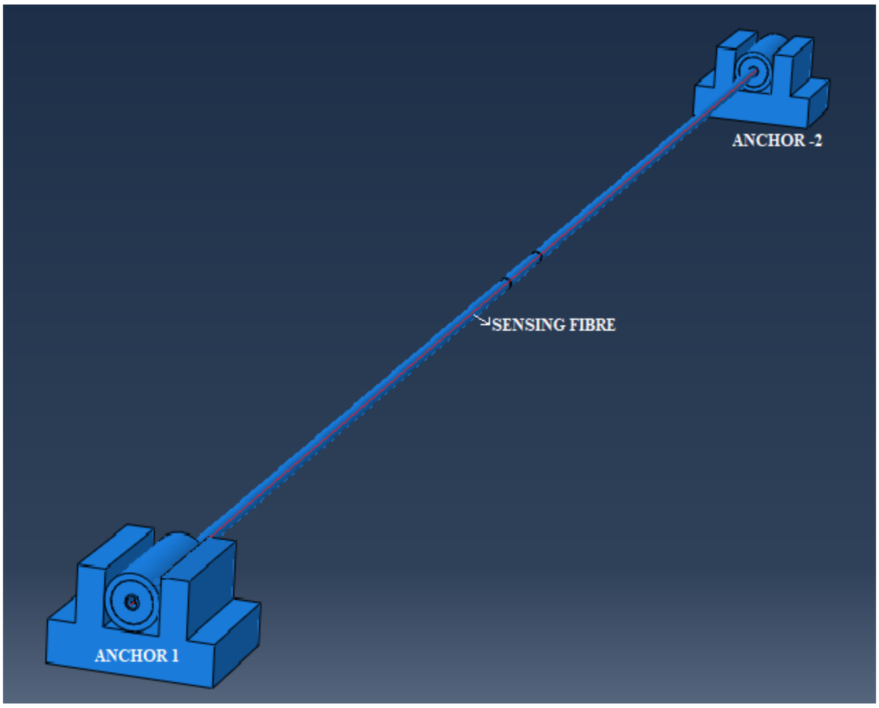
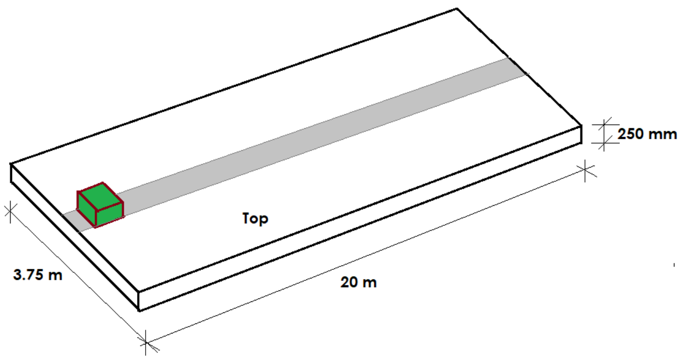
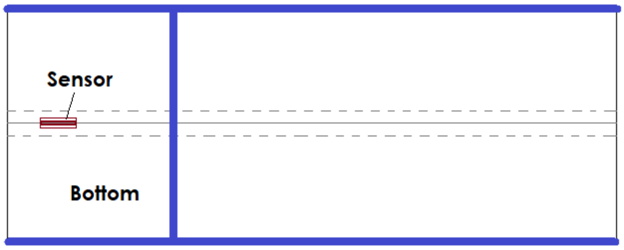


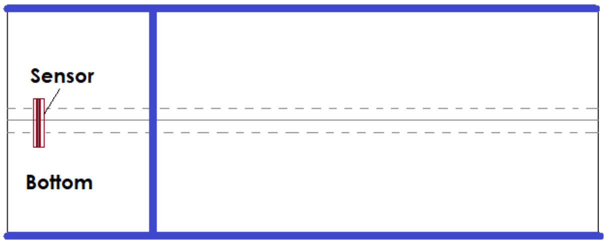
Figure. 5 Simple long gauge FBG sensor



(a) Schematic Diagram of the validation model



(b) Case 1: Long gauge sensor aligned lengthwise at the bridge-deck bottom

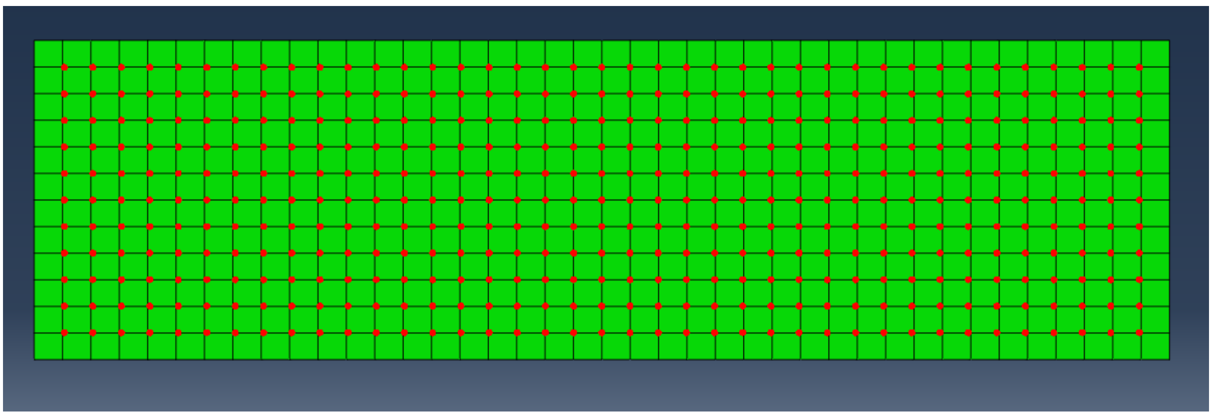


(c) Case 2: Long gauge sensor aligned lengthwise at the bridge-deck bottom

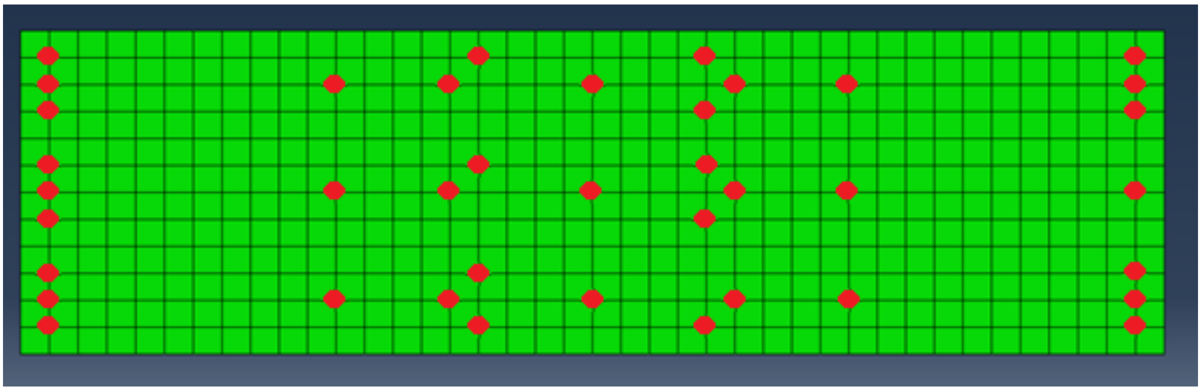
Figure 6. Validation Model for determining the optimum orientation of the Long gauge FBG Sensor

5. Results

The displacements of 429 nodes from the 30 mode shapes are extracted from the finite element model and Effective Implementation Method (EIM) is applied to these, to obtain the 40 most optimal locations for sensor placement. Figure 7(a) shows all the node locations and figure 7(b) shows the optimal sensor locations after the application of EIM algorithm. The orientation of the sensor is derived as along the breadth of the slab. This has further been validated by the results of the finite element model of the long gauge FBG sensor under moving load. The strain in the fibre in Case 2, is almost 2.7 times that that in Case 1. This result is in tandem with those obtain from OSP, that the optimum sensor orientation should be along the breadth of the bridge deck. The resulting strain contours in the sensing fibre from the validation model are shown in figure 8.

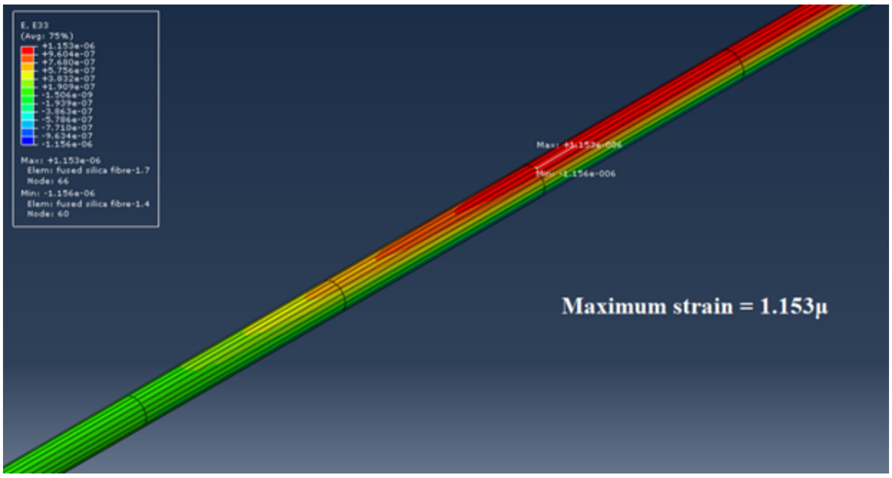


(a) Initial probable sensor locations

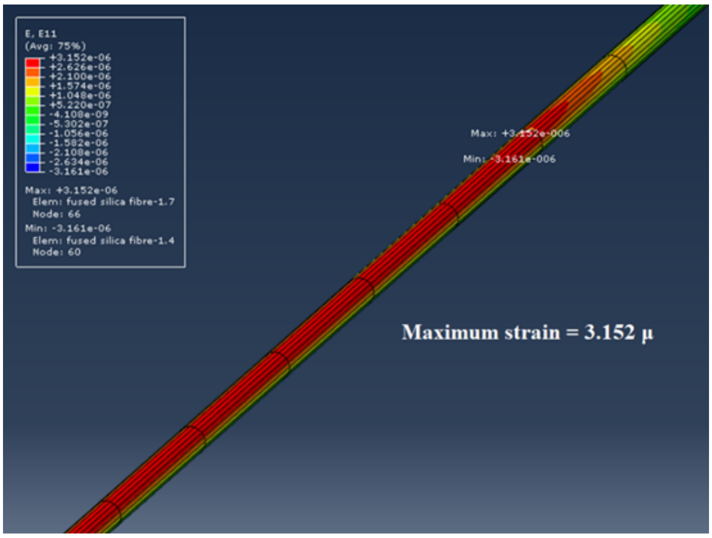


(b) Sensor locations after optimization with EIM

Figure 7. Finite element model of the bridge-deck with sensor locations



(a) Case 1



(b) Case 2

Figure 8. Strain contours in the sensing fibre in the validation model

6. Conclusion

In this study, the optimum locations and orientation for long gauge FBG sensors for application on a real-life bridge in Poland, is derived with the help of an optimization algorithm EIM. The results obtained thus are verified with a finite element model of the structure. It has been seen that the transverse orientation of the sensors will be more sensitive to the deformations on this particular bridge deck. It is also seen, that for a regular structure as in this particular case, the optimum sensor placement thus achieved is in line with the regions showcasing maximum deformation obtained from the basics of structural mechanics. However, for a complex structure, this OSP algorithm can be effectively used to predict the optimum number of sensors to be employed. It is also to be noted that the strain value sensed in the long gauge sensor is less in absolute term, because the finite element model represents undamaged bridge-deck structure under moving load. A damaged bridge deck, with inherent discontinuities, will induce increased strain value in the sensors under the same loading conditions and thus can be effectively identified as an early warning before failure.

7. References

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Acknowledgments

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