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STRUCTURAL HEALTH ASSESSMENT (SHM)

OF BRIDGE STRUCTURES

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ABSTRACT

Smart Structural Health Monitoring (SHM) gives an insight of technological advancements associated to monitoring and evaluation of civil infrastructures especially the long-span bridges. This exclusive technology develops a smart and sustainable system, examines the structural and operation safety concerns of the buildings and bridges, on the basis of which prior information or warnings are issued to address the damages and deterioration of structures. This system helps to avoid the catastrophic collapse and upmarket necessary structural repair or strengthening.

This research involves two parts. First part (Ch. 1, 2, 3) will highlight the introduction of SHM systems, some previous work done on it, its applications, advancement of SHM system along with its advantages, different phases of SHM system and then summary of its applications for bridges. Whereas the second part (Ch. 4,5,6,7) highlights the deployment of SHM system in case of bridges, while considering the identified prone zones of a structure. It will cover the application of SHM system to bridges, the hierarchy of its workability, analysis of the data retrieved from the smart systems and recommendations for pre-alarm and safety evaluation system. This system will result in Decision Making of strengthening methodologies needed for the structure on the basis of which strengthening design for a portion of bridge will be done, which will be the second part of this research.

Research work is supported by considering a real life problem of an existing reinforced concrete box-girder bridge. Identification of critical zones of the structure is the base of SHM system h author will use the structural analysis data (stress, strain, deflections, temperature intensity variations ects, etc.) recorded after the static analysis of the bridge using AXIS VM FEM software along with the results of destructive and crack analysis tests (NDT). This domain involves computer aided applications integrated with some destructive and non-destructive testing along with the crack analysis of the bridge. This research will use the static analysis data of bridge to calculate the modal parameters for installation of sensory system. This analysis will help to identify peaks of every measurement, which will give an idea about the modelling of sensor system across the bridge as every peak will be showing the maximum extent of data at a particular location so that location will be a perfect point for installation of sensor. In this way potential zones will be marked where sensors should be installed to monitor the structural health permanently. This model is based on the use 5 different types of sensors (Displacement sensors, Strain sensors, Temperature sensors, and Humidity sensors, and Weighing sensors) which are recommended to install. Thus,

result of this approach will be a SHM model that can provide the information on the durability of the structure, evaluation of structural integrity, structural reliability analysis and ensure the proper maintenance and planning along with the safe functionality of bridge. This SHM model can also account for the possible reasons of certain damages to structure because when long term data is available then possible variations are the causes of damages. At the end I will also highlight some future aspects of SHM system and the extension of this research work for the next phase.
Following bridge will be the subject of this research work.

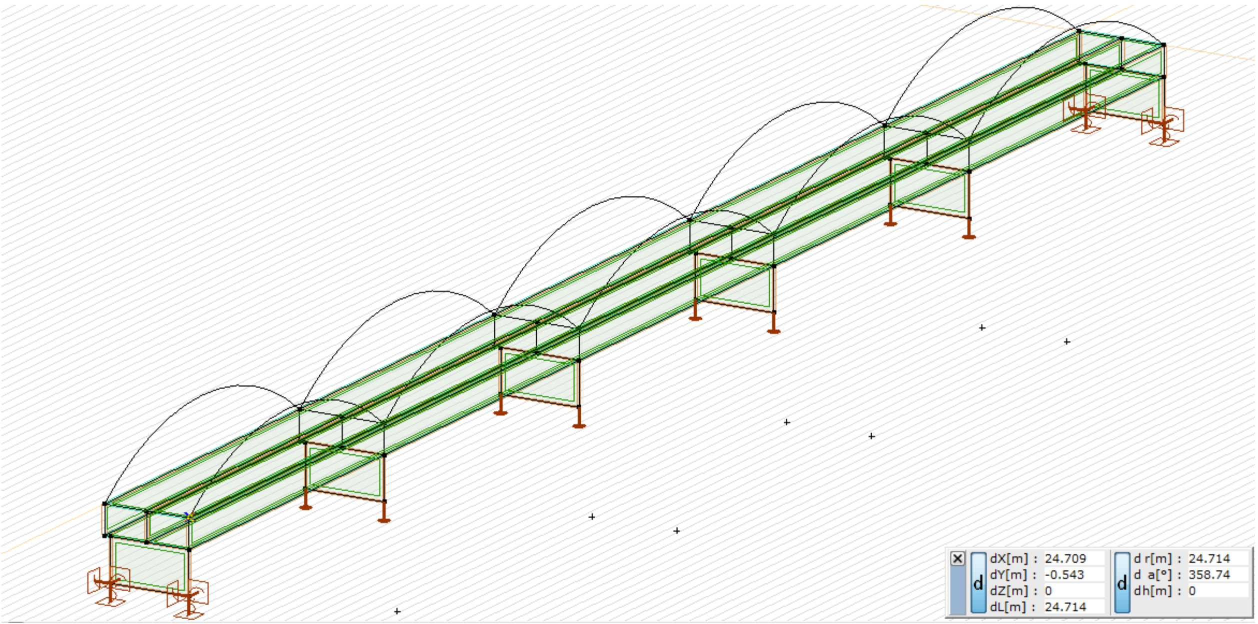

Figure 1- Axis Model of Bridge subjected to SHM

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CHAPTER 1

INTRODUTION

1.1 Problem Statement

All structures like bridges, wind energy plants, water, gas and oil pipelines, tunnels, oil rigs, pavements, rails are subjected to various internal and external damaging factors which may cause wear and tear of structures and certain malfunctioning of those systems. There are a number of causes for these damages for example due to deterioration of materials, an incorrect construction process, lack of quality control or an extreme situation resulting from an accident or environmental load. To be able to observe these changes in the material and to react in a proper way before serious damage is caused, the implementation of a damage identification system is crucial and it will be better if this system is technologically more advance and up to date. This kind of monitoring of structural behaviour can detect anomalies in time, thus enabling maintenance and repair actions to be implemented more efficiently, with a direct impact on the reduction of operating costs.

1.2 Objectives

Research work involves following objective

i. Review of SHM system by summarising the literature available on it
ii. Identification of different components of SHM system.
iii. 3D static analysis of a bridge using Axis VM software
iv. Identification of critical zones of structure with respect to deflection, bending moments, axial stresses and temperature intensity variations.
v. Installation of sensors at the critical zones of structure.
vi. Modelling of SHM system for the whole span of bridge using the location identified by the axis VM software.

CHAPTER 2

LITERATURE REVIEW

Smart Structural Health Monitoring (SHM) is an emerging technology which integrates the advanced sensor technology with the knowledge of material/structural damage characteristics to monitor the condition of structures in real time while in service. Recent advancement in sensing technologies and the characteristics of materials and structures combined with developments in the fields of communication and computations have resulted an interesting development in diagnostic technologies for monitoring the integrity of structures and also for identifications of potential damages to both the existing and new structures in reality with the less involvement of human efforts. Using certain sensors to monitor the real life conditions of in service structures becomes feasible if sensor signal can be interpreted accurately to reflect actual condition of structures through real time data processing. This whole system has the flexibility to absorb the modification of automation and integration to perform real time inspection and damage detection.

2.1 Literature

With the economic development of society, long-span bridges have become the art and the necessity of the day therefore many such bridges have been built or are under construction. i.e., the Akashi Kaikyo Bridge having a span of 1991 m in Japan, the Xihoume Bridge with a main span of 1650 m in China, the Great Belt Bridge having the main span of 1624 m in Denmark [1, 2]. All of these bridges should satisfy the basic serviceability, safety and sustainability requirements during their life span. However, environmental changes, such as stronger hurricanes, earthquakes that cause faster material deterioration, cause many challenges for long-span bridges. A number of long-span bridges had been destroyed because of some natural and man-made hazards. For example, the famous Tacoma Narrow Bridge collapsed as a result of strong wind [3], the I-35W Bridge in USA collapsed in 2007 in which the collapse was initiated by buckling at the portions which were connecting the diagonal members under compressive axial loads, and the Wenchuan earthquake occurred in China in 2008, caused the collapse of many bridges [4]. In most of the cases the deterioration of different structural elements like arch rings, arch column, tie rod or hanger rod of an arch bridge is due to excessive vehicle load, environmental hazard, man-made hazard and their combined effects. The serviceability, safety and sustainability of the long-span bridges is the most addressed issue in the current scenario. A Structural Health Monitoring (SHM) system that is used for surveillance, evaluation, monitoring and assessment of existing conditions of long-span bridges has been widely developed and even on the way to its more advancement, and the recently-developed long-term SHM system is the most emerging support system for monitoring the safety, serviceability, and sustainability of long-span bridges [5].

There are some conventional non-destructive examination (NDE) techniques that somehow provide information about the existing condition of the structure but SHM system takes advantage of new sensing technologies that have been developed a lot over the past few decades. Fiber Optic Sensors (FOP) and wireless techniques have been widely used in this system because they have the advantage of their applications, which are characterized by a difficult access to the structure [6, 7]. The smartness and miniaturization of sensors, represented by the so-called Micro Electro-Mechanical Systems (MEMS) has also received much attention [8]. M/s Intelligent Sensing for Innovative Structures (ISIS, Canada), has equipped up to six bridges with fibre optic sensing systems that allow remote monitoring of the structures since 1993 [10]. The Siggenthal Bridge in Switzerland is a masterpiece of this emerging technology. This bridge is an arch bridge having the main span of 117 m, having 58 installed FOPs [11]. There are some other examples such as the Ebian Dadu river arch bridge in China [12], the Flexi-Arch in United Kingdom [13], the Versoix Bridge in Switzerland [14] and the Yonghe Bridge in China [15]. The installation system adopted the same technology of FOP sensors. The recent researches in the field of sensors have revealed that FOP sensor has a long sensing range, which makes it capable of providing the strain or temperature variations at every spatial resolution along the entire sensing fibre, imbedded in or attached to the structures. Using the fibre itself as the sensing medium, have affirmed that FOP sensors are more accurate and reliable than other traditional sensors (i.e., strain gauge) [16–19] that’s why these sensors will also be recommended in this research also.

Wireless sensors have also been widely installed as SHMs of bridges [20–22]. Wireless Sensor Networks (WSN) for bridge monitoring provides an expert guidance for structural monitoring of both existing infrastructure and new construction projects. The purpose of this guide is to develop a generic methodology for the design and implementation of WSNs for monitoring of civil infrastructure, coupled with best practice for data management and information evaluation.

Advantage of the new sensing techniques has revolutionized the long-term SHM systems for long-span bridges. A SHM system has been implemented on the second World’s longest bridge, The Lupu bridge, which is a steel half-trough tied arch bridge. The temperature, strain, acceleration, and wind effect of the bridge were monitored and analyzed by the installation of different sensors constituting the SHM system [23]. Alamdari et al. [24] have presented his research on a large scale SHM application on the Sydney Harbour Bridge, which is also an arch bridge with a main span of 503 m. The performance and structural damages of a subset of 800 jack arches under the traffic lane 7 were analyzed on the basis of SHM data. Magalhaes et al. [25] also developed a SHM system for the Infante D. Henrique Bridge, which is a concrete bridge in Portugal with main span of 280 m, they installed this system to evaluate the usefulness of approaches based on modal parameters tracking for SHM of bridges.

Ding et al. [26] investigated a high-speed railway arch bridge, the Dashengguan Yangtse River Bridge in China in order to analyze the dynamic characteristics of the hanger vibration. This investigation was also based on the data measured from a SHM system.

This technology is getting boom day by day as many other SHM systems have also been installed in long-span bridges [27–29]. Typical examples include the Sutong bridge (1088 m, a cable-stayed bridge in China) [30,31], the Tsingma bridge (1337 m, a suspension bridge in Hong Kong) [32], the Tatara Bridge (890 m, a cable-stayed bridge in Japan), the Akashi Kaikyo Bridge (1991 m, a suspension bridge in Japan) [33], the Great Belt East Bridge (1624 m, a suspension bridge in Denmark) [34], the Normandie Bridge (856 m, a cable-stayed bridge in France) [35], the Commodore Barry Bridge (548 m, a truss bridge in USA) [36], and the Confederation Bridge (250 m, a box girder bridge in Canada) [37]. More than 80 bridges had been equipped with SHM systems by the year of 2016 in Hong Kong and China [17].

These SHM systems have advanced our understanding about the development of a long-term system. More importantly, the data observed from the SHM systems can be utilized for evaluating the serviceability, safety, and sustainability of long-span bridges. Many researches have been done for identification, damage detection, model updating, safety evaluation and sustainability assessment of long-span bridges by using the above mentioned system. Rainieri and Fabbrocino [28, 38–41] used modal-based damage detection algorithms to identify civil structures modal parameters based on the data observed from SHM system. On the basis of SHM data, the reduced-order models of a dynamical system have been proposed and updated. Using the application of data observed from a SHM system of a long-span arch bridge, Comanducci et al. [43] have presented applications of different vibration-based damage detection methods by using up-to-date multivariate statistical analysis techniques.

The results focusing the assessment of the minimum detectable damage severity, using different techniques, are anticipated to contribute a more aware use of monitoring data and rely over the related health state assessment information. Li et al. [44] worked for the investigations and damage detection of a streamline bridge model by using SHM observed data. Li and Ou [45] and Li et al. [46] have diagnosed the condition of bridge and summarized bridge health based on SHM systems. The significance of this system can be easily visualized from the fact that 102 papers, concerning the importance of smart structural health assessment, were presented in an International workshop held at Stanford University in September 1997. Technical presentations made by the researches and experts of this field highlighted the importance of this system by discussing the advancements in sensing technology, modelling and diagnostic methods, system integration and applications.

2.2 Review of Literature

The recent development of modern technology for information and communication system, signal processing internet and structural analysis significantly revolutionized the application and improvement of the SHM systems. Despite of this extensive research on SHM, there still exist some hidden parts of this research, which need to be addressed in the future, such as the improvement of the accuracy of a sensory system, high-frequency and accurate data sampling, data mining and knowledge discovery, diagnostic methods, the analysing and modelling the big data observed from the SHM system utilized for decision making on maintenance and management. By keeping in mind the applications of SHM system this study explores the ways and mean to establish this system. Installation of SHM over a bridge is the main objective of this research work through which advancements of the SHM can be seen. SHM system installation can be based on any damage detection data or on the analysis of structure. Previous researches have shown that most of the time damage detection data was used to establish a new SHM system where as in this research structural analysis data will be used to model this system. The selection of a particular domain for analysis of bridge structure, was also a major concern for which applications of Axis VM software provided the solution of this problem. So this study is divided into two sections. Section 1 (Ch. 1, 2, 3) briefly introduces the SHM systems, some previous work done on it, its applications, advancement of SHM system along with its advantages for long-span bridges, different phases of SHM system and then summary of its applications for bridges.

Section 2 (Ch. 3, 4, 5, 6) reviews the real life example of an existing bridge for which SHM is to be modelled using the analysis data of this bridge. Analysis is done through the Axis VM software, destructive, non-destructive testing and crack analysis study of the bridge, which identified the structural defects and using that data, SHM model is designed for the actual bridge. On the later stages strengthening of this bridge is also planned.

CHAPTER 3

ANALYSIS METHODOLOGY

In order to model the SHM system the author is carrying out the static analysis of an actual bridge structure (for complete details of bridge see Sec 4.1) using the AXIS VM software supplemented with destructive, no-destructive and crack analysis tests. This analysis involves the identification of critical maximum and critical minimum valued zones of deflections, axial stresses, strains, shear forces, and bending moments. These zones will highlight the necessity of sensor installation which is the base of SHM system. We also need to identify the strength of RC as the strengthening of this structure is also planned in the future for which destructive and non-destructive tests were performed. In order to identify the cracks along the structure which are mainly due to shrinkage of concrete, crack analysis is also done so that potential zones for installation of shrinkage devices can be identified.

3.1 The Structural Health Monitoring Process

It's been believed that the SHM problem is fundamentally a process of statistical pattern recognition. Therefore, the damage detection studies are summarized in the context of a statistical pattern recognition paradigm. A long-term SHM system should include at least five integrated sub-systems [30], which are shown in the following figure.

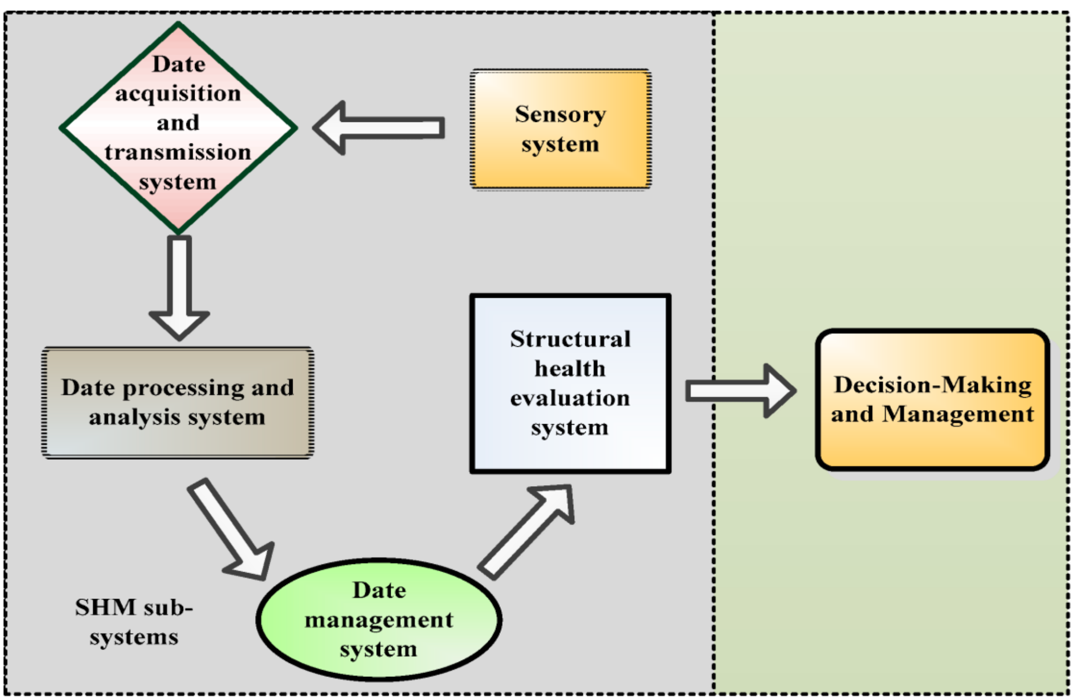


Figure 2- Subsystems of SHM System

3.1.1. Sensory System

Variable type, the sensor type, and the positioning of the installation of sensors are the main aspects which are considered in this system. Variables include load and environmental actions (vehicle load, wind load, earthquake ground motion, vessel collision, temperature, humidity, etc), global response (acceleration and deformation), and local response (strain, cable tension force, displacements of joints and bearings, crack and fatigue of elements). Based on the variables in a SHM system, 11 different type of sensors should be installed in such a way that they can measure: vehicle loads, wind speeds & direction, environmental temperature & humidity, vibration, structural temperature, strain, main beam deflection, bearing displacement, and cable tension force. In this research work only 5 sensors (temperature, weighing, displacement, strain, temperature and humidity sensors) will be used for considering the scenario of the bridge.

3.1.2. Data Acquisition and Transmission Sub-System

This system involves the selection of data acquisition devices and method, sampling modes, and the transmission technology. From the above studies, a framework for data acquisition and transmission system is highlighted in figure 3. This system is very simple in which sampling rate for dynamic signal should follow the Nyquist Shannon sampling theorem.

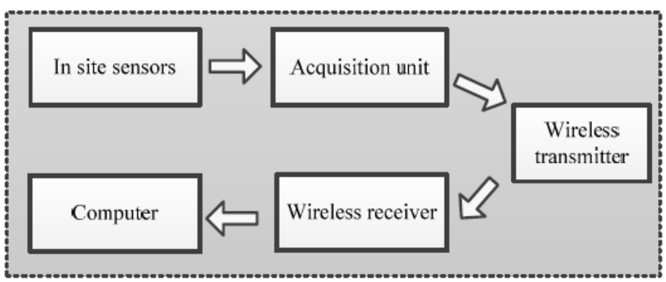


Figure 3- Framework of Data Acquisition and Transmission System

3.1.3. Data Processing, Management, and User Interface

Data processing and management system can process all dynamic and static data during the whole life cycle of a bridge, including the query, storage, etc. of the data. It then process the information to user interface. Based on this system, remote monitor of full-bridge can be achieved. Data processing and management centre includes server group, central network switching equipment, and server maintenance equipment, optic fibre grating strain acquisition station, workstations and other similar equipment.

3.1.4. Evaluation of Measured Data

The safety of the bridge can be then evaluated according to the measured stresses, strain, deformation, temperature and cable force signals data at the designated portions of the ridge. This evaluation is the backbone of SHM system because it makes the monitoring process fully functional which becomes intelligent enough to give early warning via an alarm monitoring scheme in real-time. This system sends monitoring report on a daily basis. Once an early warning signal is generated, the alert would be released.

CHAPTER 4

PRACTICAL DEPLOYMENT OF SHM SYSTEM ON A BRIDGE

4.1 Introduction to the Examined Bridge Structure

Bridge structure that is taken under consideration for this research work is suffering some strengthening issues for the last few decades. Strengthen work as be done on the mentioned bridge a couple of times thus it’s been consider to model a SHM system for this bridge so that continuous monitoring of bridge structure can be done. The bridge is situated in northern part of Hungary. Overall bridge structure contains five spans of each of 27.6 m making the total length of 138 m. It is a continuous reinforced concrete box girder having a 20 cm top slab and 16 cm bottom slab. Both of these slabs are joined using the RC walls of 40 cm thickness. Overall cross section has a height of 7×2.71 m which is resting on wall support. Cross section of the bridge is shown in figure 4.

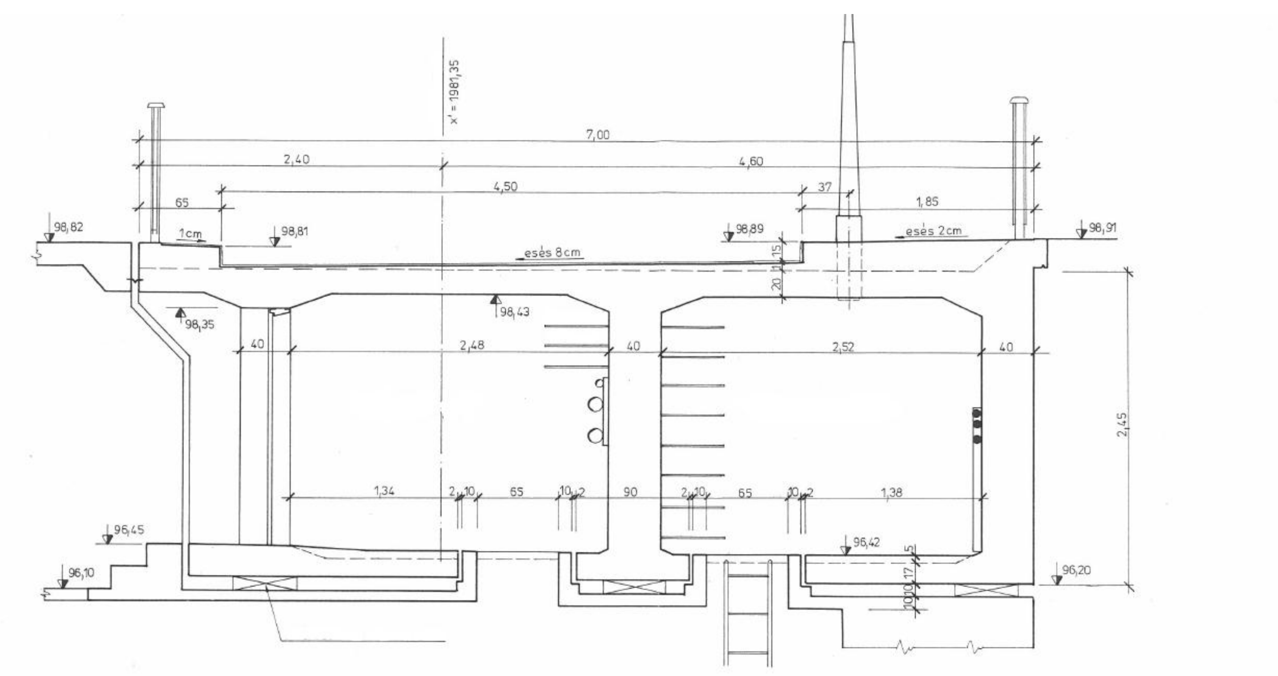


Figure 4- Cross Section of the Analysed Bridge

4.2 **Strength Evaluation of Bridge**

4.2.1. Destructive Tests

Destructive tests were carried out by the people who worked earlier for strengthening of this bridge. That data was retrieved from them with the help of research consultant. It involves the compressive strength testing of concrete samples. For this test sample extraction is a major task. In this regard 7 cores were extracted from the wall of the bridge structure. These cores were then cut to prepare a sample of 90 mm diameter with a height of 180 mm. The density of concrete samples was specified between 2254-2358 kg/m³. These samples were then tested in the compression machine. The average compressive strength was measured to be 17.5 N/mm² and the relative deviation was measured to be 27%. Typical compressive strength was measured to be 10 N/mm², which means that concrete is of class C10/14 so its strength is below the designed value. The results of these tests are given in table 1.

Table 1- Destructive Test Results

Mark	**Size**	**Weight**	**Density**	**Pressure**	
	mm	**gs**	**Kg/m³**	**Force (KN)**	**Strength (N/mm²)**
I	180/90	2677	2338	115	18.1
II	180/90	2642	2298	72	11.3
III	180/90	2662	2316	118	18.6
IV	180/90	2781	2419	166	26.1
V	180/90	2656	2311	92	14.5
VI	180/90	2591	2254	94	14.8
VII	180/90	2711	2358	120	18.9

4.2.2. Non-Destructive Tests

Non-Destructive strength tests were also performed on site to check the instantaneous compressive strength of the concrete. These were also performed to countercheck the results of destructive tests of the concrete.

Non-Destructive test, used to measure the compressive strength of concrete, is performed by using the Schmidt-Hammer. It is also known as Schmidt-Hammer or rebounds test because to measure the strength of the concrete we have to strike the Schmidt Hammer at certain locations of the

specimen. Schmidt hammer measures the average rebound value of the measurement and the compressive strength in the vicinity of each test site
by calculating the impact value of specimens (see Table III). This impact value is also known as rebound value. This rebound value is then checked through a calibrated non-destructive evaluation graph (different for different positions) given on the hammer to find the relevant compressive strength.
Total 9 tests were performed with 216 measurements. The average compressive strength value of the cylinders, measured on the spot was 17.5 N/mm² with an average rebound value of 48.4. The relative variance was between 22-27%.
Measurement sheet of NDT test is summarized in table 2.

Table 2- NDT Results Summery

Mark	**Size**	**Weight**	**Density**	**Pressure**		**Average Rebound Value**
	mm	**gs**	**Kg/m³**	**Force (KN)**	**Strength (N/mm²)**	
I	180/90	2677	2338	115	18.1	46
II	180/90	2642	2298	72	11.3	46
III	180/90	2662	2316	118	18.6	55
IV	180/90	2781	2419	166	26.1	45
V	180/90	2656	2311	92	14.5	46
VI	180/90	2591	2254	94	14.8	48
VII	180/90	2711	2358	120	18.9	52
Average Value					17.5	48

- **Key Notes**

Based on the destructive and non-destructive tests results, it can be stated that the strength of the concrete is low with a high relative dispersion so less strength can produce more deflection which is to be monitored therefore after the analysis of bridge we can define the locations for deflection measuring sensors.

4.3 Crack Analysis

A detailed crack analysis was carried out by taking the images of bridge sections having potential cracks. They are analysed through the bridge. Most of the cracks could be seen on the side walls of the bridge structure (Figure 5). There were only a small number of cracks on the top of the structure. There were a few cracks visible along the lower part of box-girder cross-section but there are no cracks between the side walls (main supports).

Most of the cracks in main supporting parts (side walls) of the structure were on the lower connecting plates but they did not reach to the top. There were some cracks along the middle opening too. These cracks were somehow vertical thus they did not reach to the supports because while approaching the supports they turned upside down.

The width of cracks in many cases exceeded the value of 0.4 mm, which was considered as the limit value. The cracks on the sidewall which are close to the pathway were wider than the cracks going downward.

The main causes of these cracks are the effects of temperature changes, and shrinkage. These effects are further analyzed by the AxisVM model of the bridge where it will also be easy to understand that where we need to install the sensors for measurements of temperature and shrinkage.

Figure 5 Cracks Along the Side Wall of Bridge

CHAPTER 5

STATIC ANALYSIS OF BRIDGE USING AXIS VM SOFTWARE

5.1 **Axis VM Introduction**

AxisVM is Finite-Element software for the static, vibration, and buckling analysis of structures. It was developed by and especially for civil engineers. AxisVM combines powerful analysis capabilities with an easy to use graphical user interface.

AxisVM involves many modelling tools including geometry tools (point, lines, surfaces), automatic meshing, material and cross-section libraries, element and load tools, import/export CAD geometry (DXF), interface to architectural design software products like Graphisoft's ArchiCAD via IFC to create model framework directly. At every step of the modelling process, you will receive graphical verification of your progress. Multi-level undo/redo command and on-line help is available. After modelling of structure we can analyze the Static, vibration, and buckling of the structure.

In my case I will first develop the Finite Element Model of one span of the bridge and perform a static analysis of this structure.

5.2 **FE Model Using AxisVM Software**

The bridge is modelled as per the mentioned cross section. Out of its 5 spans we will model two of the spans only. Analysis results of its two spans can be extended to full length of the bridge. In the construction state, the box girder's cross-ribs are like two-ply supports series carry their self-weight and live load, moving load, temperature or thermal loads, and other durable loads (layer weight, etc.). Wind, earthquake and snow loading are not considered in this case because they are not effecting the structure very much. Model involves the formation of geometry (using the drawing tools), assignment of elements using the domain command, application of loads, and generation of meshing (using domain meshing with an average mesh element size of 1 m). At the end we can analyse the results by running static analysis.

5.2.1 **Geometry**

Geometrically model is formed by constructing 5 elements. Two of them are the surface plates (upper and lower of the beam) using its span length and width having cross section of 27.6×7 m with a thickness of 20 cm and 16 cm. Three elements are the walls connecting upper and lower plates with a thickness of 40 cm. These elements are supported by line supports out of which one of them is fixed at one side and pinned on the other where the middle support is roller.

5.2.2 **Loads**

The next step involves the application of different loads on the constructed model. These Loads involves following five types of loads

1. **Live Loads**: Live loads are applied on the surface of the model as a domain loads with a value of 7 kN/m² on one side and 4.5 kN/m² on the other side which is open for traffic.
2. **Dead Loads**: Dead loads are the self-weight of its elements that can be calculated from its geometry so the self-weight is applied as dead load having value of 1.9 kN/m² on the top slab and 0.42 kN/m² on the bottom plate.
3. **Moving Loads**: Moving loads include the vehicular which are applied as a distributed load with a value of 300 kN.
4. **Barrier Loads**: There is also a barrier at the side of the bridge so its load is also applied as a distributed load with a value of 1 kN/m².
5. **Temperature Loads**: Temperature loads are also applied by considering the thermal effects and shrinkage with a maximum and minimum values of 40 °C and -40 °C temperature.

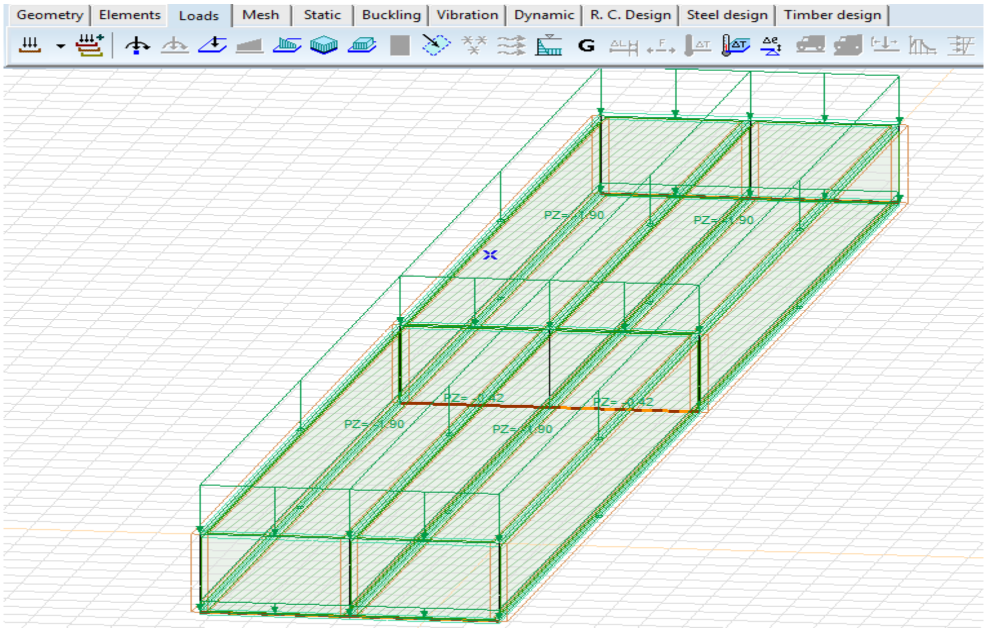


Figure 6- Axis Model of Bridge with Dead Loads

5.2.3 Materials

1. **Quality of Concrete**: C10/14 **(**Side Walls, bottom plate, top plate). Analysis is based on destructive and don-destructive testing results.

   Compressive Strength: fcd= 7.0 N/mm²

   Tensile Strength: fctd = 0.65 N/mm²

   Initial modulus of elasticity: E_{cd} = 24 900 N/mm²

   Modulus of elasticity (long-term loads) Ec = 10 000 N/mm²

2. **Quality of Steel Reinforcement**: S360

   Yield Strength: fyd = 310 N/mm²

   Modulus of elasticity: Es= 200 000 N/mm²

5.3 Static Analysis Results Summary.

Following table shows the maximum and minimum values of the parameters which are of our major concern for locating the positions of installation of sensors along the bridge. Results are showing the critical max and critical min values of each parameter for two spans. These can be extended to the full length of bridge.

1-Displacements

Table 3- Static Analysis Displacements

	Translations (mm)			Rotations (rad)		
Section I & II	eX	eY	eZ	eX	eY	eZ
Critical Max	0.462	0.250	-2.085	0.00027	0.00038	0.00004
Critical minimum	-0.320	-0.031	0.013	-0.0003	-0.00036	-0.00003

2- Surface Internal Forces

Table 4- Surface Internal Forces of Static Analysis

Parameter	Notation	Critical Max	Critical Min
Membrane Force in x-direction,	nX (KN/m)	7029.447	-7493.23
Membrane Force in y-direction,	nY (KN/m)	3891.39	-5947.67
Membrane Shear Force	nXY(KN/m)	4375.116	-3607.25
Flexure Moment about x-direction,	mX (KNm/m)	710.79	-696.9
Flexure Moment about y-direction,	mY (KNm/m)	539.66	-642.9
Specific Torsional Moment	mXY (KNm/m)	462.78	-451.19
Resultant Shear Force	vED (KN/m)	4128.32	0.014

3- Surface Stresses

Table 5- Surface Stresses of Static Analysis

Parameter		Notation	Critical Max	Critical Min
Axial Stress in x-direction	Top	Sxx (N/mm²)	44.86	-48.36
Axial Stress in y-direction		Syy (N/mm²)	24.63	-27.88
Shear Stress-xy		Sxy (N/mm²)	26.35	-24.22
Axial Stress in x-direction	Bottom	Sxx (N/mm²)	43.01	-45.30
Axial Stress in y-direction		Syy (N/mm²)	33.19	-27.28
Shear Stress-xy		Sxy (N/mm²)	19.27	-22.55

4- Support Reaction

Table 6- Support Reactions of Static Analysis

Parameter	Notation	Critical Max	Critical Min
Reaction Force along x-direction	Rx (KN/m)	7300.84	-7355.05
Reaction Force along y-direction	Ry (KN/m)	9604.88	-10288.04
Reaction Force along z-direction	Rz (KN/m)	3548.14	-8489.48

Reaction Moment along x-direction	Rxx (KN/m)	91.72	-198.45
Reaction Moment along y-direction	Ryy (KN/m)	628.99	-662.46
Reaction Moment along z-direction	Rzz (KN/m)	655.67	-631.108

The above analysis data can also be visually observed in Sec 6.1-6.4, where the profiles of each variable are given. Based on the analysis result we can define the direction of our research work in a better way because now we are in a position to decide the installation location of the sensors. The above results provides the platform for this installation.

CHAPTER 6

SENSORS INSTALLATION

It was mentioned earlier that total of 11 types of sensors can be installed along the bridge for a fully functional SHM system. These sensors include:

i. Displacement sensors
ii. Strain sensors
iii. Temperature sensors
iv. Weighing sensors
v. Humidity sensors
vi. Wind velocity and direction sensors
vii. Pressure transmitter
viii. Lateral acceleration sensors
ix. Vertical acceleration sensors
x. Three-Dimensional acceleration sensors
xi. Pressure ring

Among these sensors the first five will be the subject of my research work because in the case of the considered bridge, dynamic effects are not considered so only the most important aspects which needs the attention on regular basis are taken into account, therefore displacement, strain, temperature, weighing and humidity sensors will be suggested to install.

6.1 Installation of Displacement Sensors.

Displacement sensors are used to measure the deflection along the structural elements. Deflection is a major concern in case of the bridge structures as the deflection value beyond its limits can lead to the catastrophic failure of structure, therefore continuous monitoring of deflection in the structure is required. By keeping it in mind for the analysis of the bridge, as per the real loading and support condition, gives the deflection along the whole span but in order to install the sensors we are just concerned to the its maximum values. As the bridge contains two upper and two lower plates so we will be concerned to the maximum value of each plate surface. These are shown in figure 7 in which span on the left is span 1 and on right is span 2.

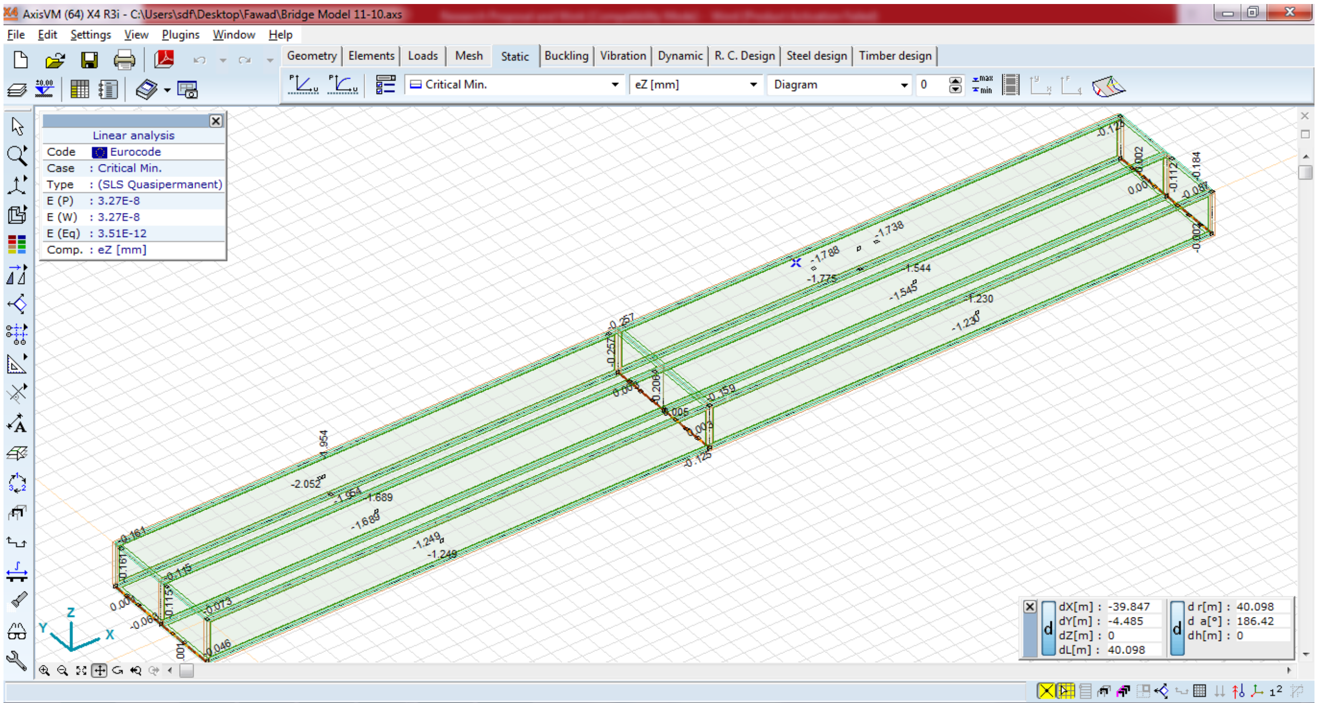


Figure 7- Displacement Profile with Critical Maximums and Minimums

Maximum valued locations of deflection for each plate are marked along the horizontal and vertical axis, which is the exact location of installation of sensor along each surface. So total 4 sensors in each span are recommended. All of these sensors will be installed externally (on the surface of concrete) on the lower side of each plate. For span 1, marked locations are illustrated in figure 8.

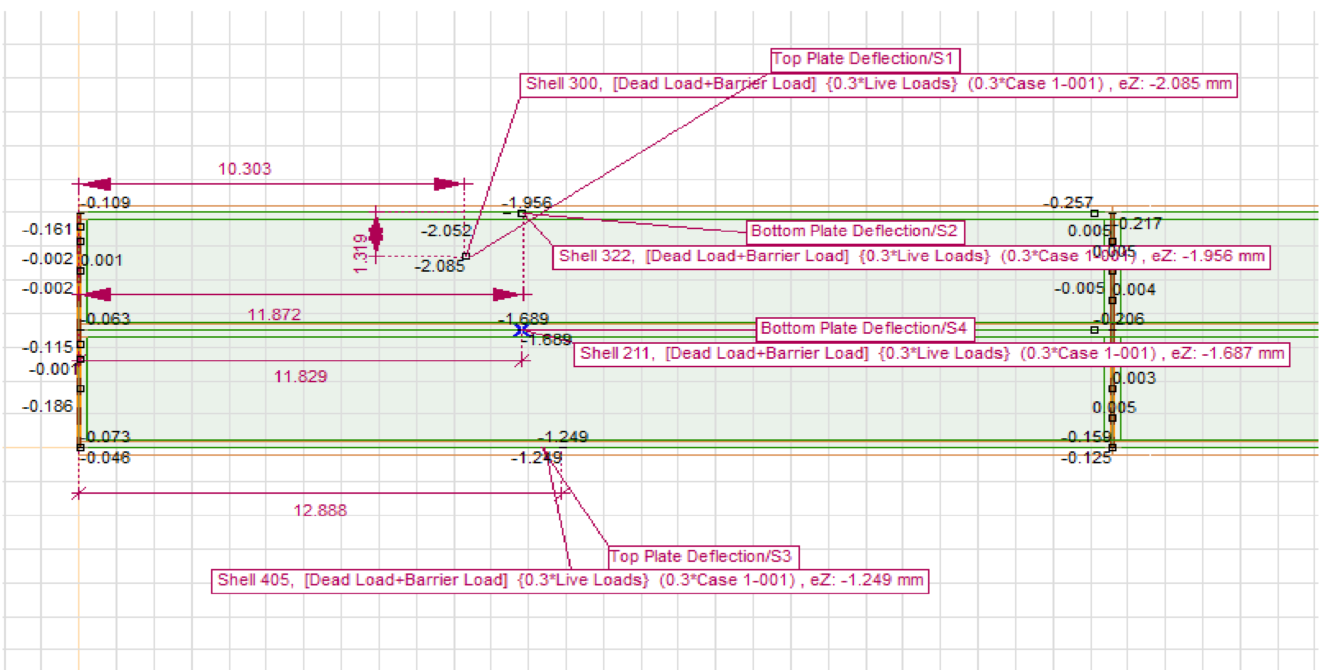


Figure 8- Displacement Sensors Locations for Span 1

For span 2 marked locations are illustrated in figure 9.

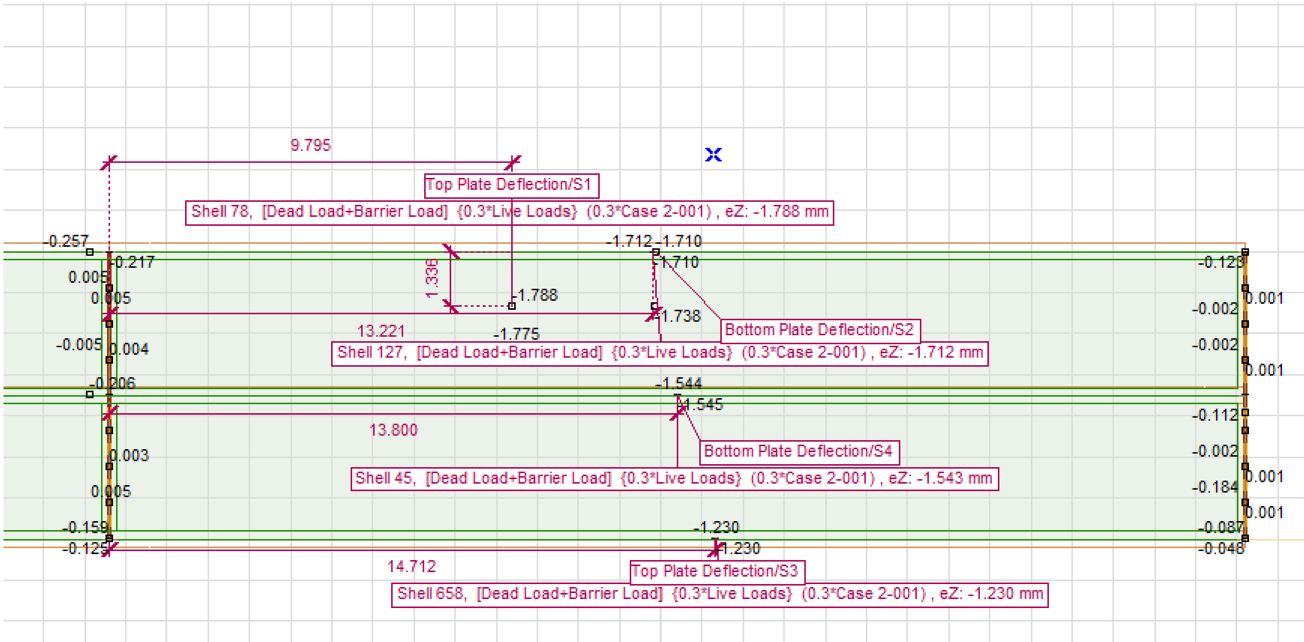


Figure 9- Displacement Sensors Locations for Span 2

For the full length containing 5 spans of bridge, total of 20 deflection sensors will be required on identified locations.

6.2 Installation of Strain Sensors.

Strain is an important and one of the basic parameter required for SHM of any structure because it directly reflects the working condition of a monitored structure. The measured strain data is very useful because it can be used for safety, sustainability, and fatigue assessment. There are many types of strain gauge, such as a traditional LVDT type strain gauge, a vibrating-wire strain gauge and optical fibre Bragg grating (FPG) strain sensors. Normal LVDT’s cannot be used for long term assessment of strain because it can have calibration problems therefore FPG stain gauge would be recommended for installation because FPG stain sensors are widely used by a SHM systems. Strain sensors use stress profile to calculate the strains as within the elastic limit stress is directly propositional to strain so maximum value of stress induces maximum strain at the same location along the bridge therefore sensors will be installed at the places of maximum valued axial stresses.

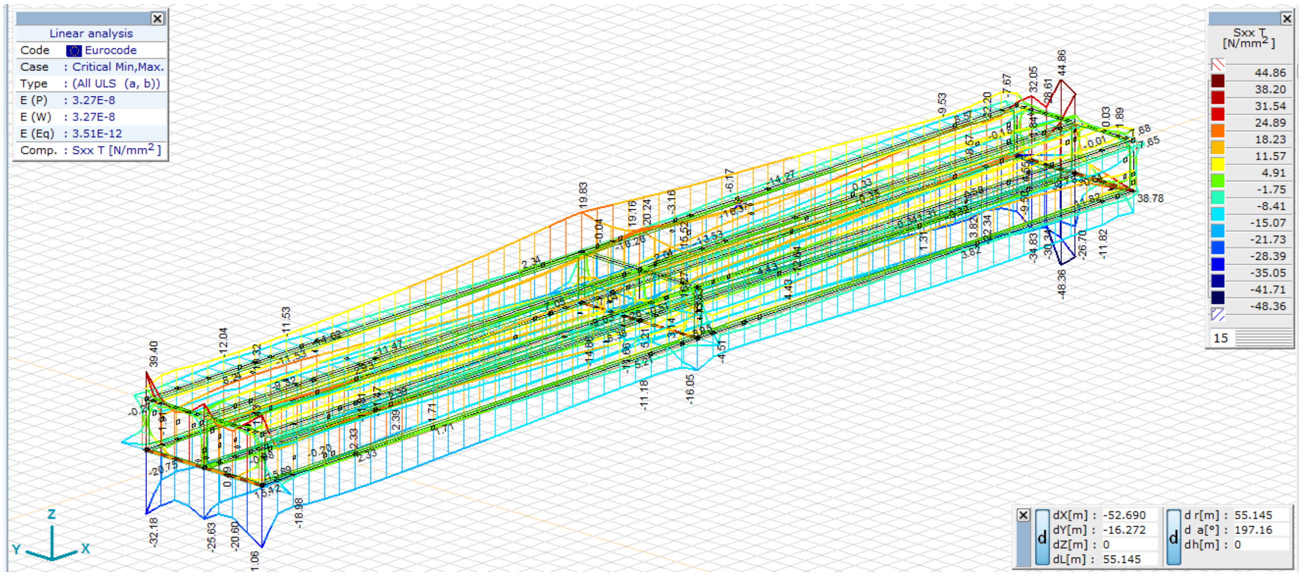


Figure 10- Axial Stress Profile of Bridge

Its worthy to mention that strain gauges should not be connected along the RC surface therefore it is recommended to uncover the portion of reinforcement at the designated locations where these sensors will be tied to steel bars (figure 11) to measure the strain data.

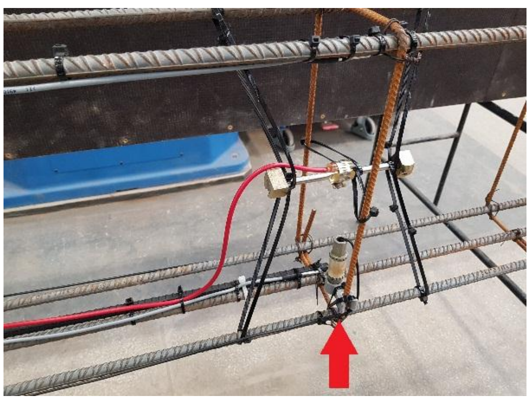


Figure 11- Example of Installation of strain sensor

Similar to displacement sensors, 8 strain sensors will be recommended for both top and bottom plates but in this case stresses for top plates have the maximum values at the central support of top plates so instead of 4 sensors, 3 sensors are recommended at the three nodes of top plates joints (see figure 12).

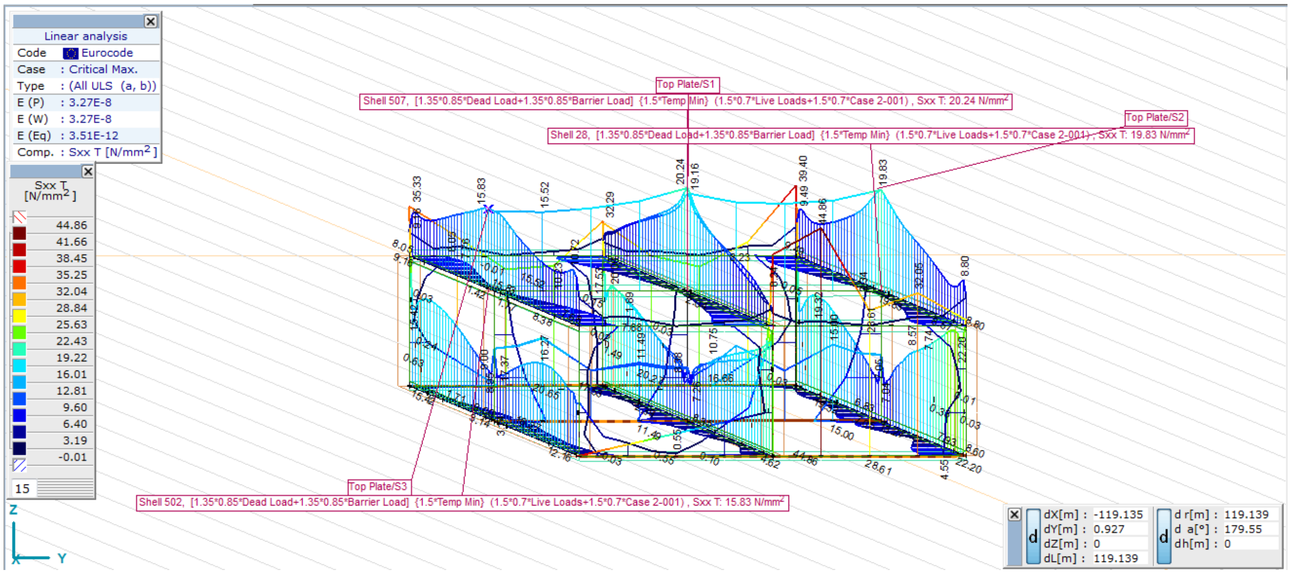
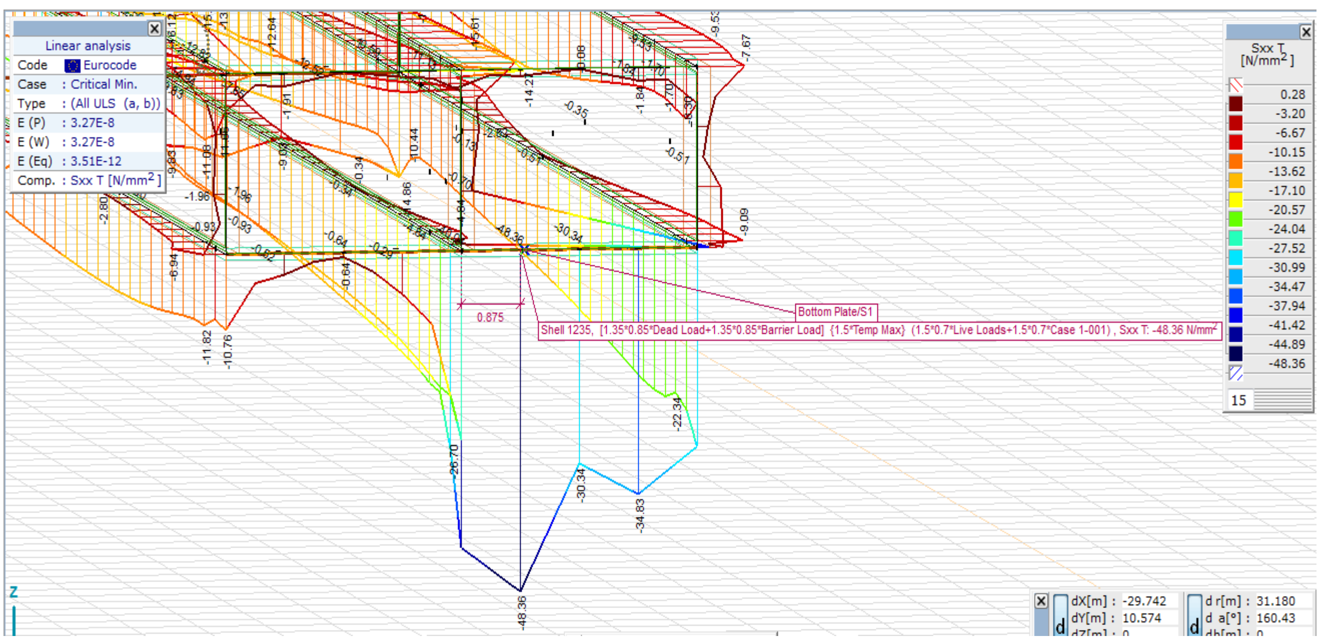


Figure 12- Location of Strain sensors at the top plates

For the bottom plates 4 sensors at different locations (shown in figure 13) are recommended. Maximum value occurred at a distance of 0.875 (see figure 13-1) m from the central support so 1 sensor will be installed at this location and rest of the sensors will be installed at three joints of bottom plates as shown in figure 13.



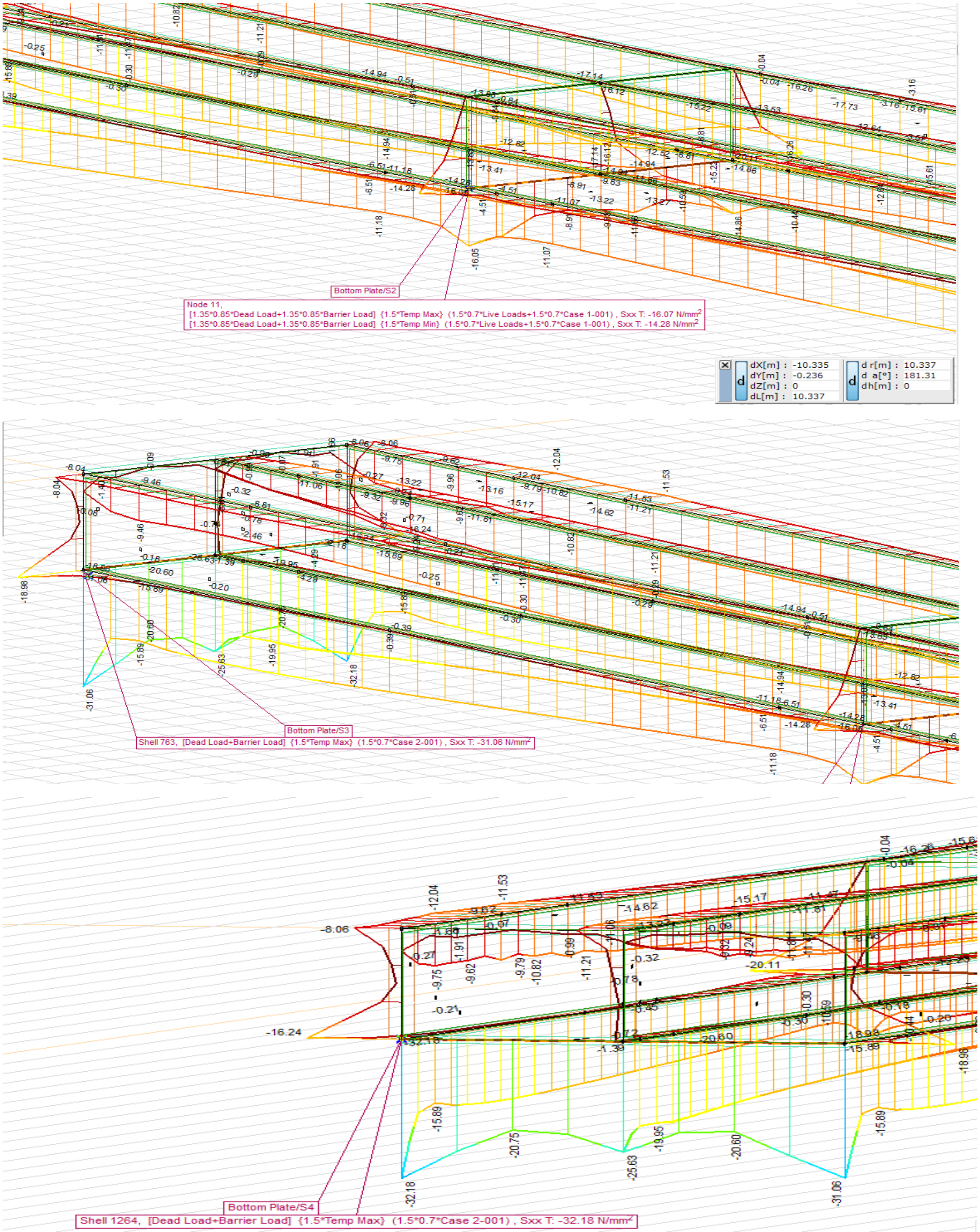


Figure 13- Location of Strain Sensors for bottom plate

6.3 Installation of Temperature and Humidity Sensors

6.3.1 Effects of Temperature

Change in temperature causes the expansion or contraction of materials. Heating causes the expansion and cooling causes the contraction. When free to deform, concrete usually expand or contract due to temperature changes. The size of the concrete structure, whether it is a bridge, a highway, or a building does not affect the rtemperature intensity variations. The expansion and contraction of concrete does not depend on the structure's cross-sectional area.

Temperature changes in the concrete may be caused by ambient environmental conditions or by the hydration of the cement. When heat cannot be dissipated in the big structure, severe problems can develop in them. Thermal contraction on the surface of concrete without the change of its internal temperature will cause a thermal differential that can lead to cracking. Change in temperature, that causes the shortening, will produces the cracks in the concrete members that are held in place or restrained by another part of the structure, internal reinforcement or by the ground. For example a long restrained concrete section is allowed to drop in temperature. In case of long restrained concrete section, when temperature drops, the concrete tends to shorten, but cannot as it is restrained along its base length. This causes the stressing of concrete and eventually leads to the cracking of concrete.

6.3.2 Effects of Humidity

In case of RC structures, concrete material constantly faces the environment changes around it, so temperature and humidity affect the moisture levels within it. Just like the importance of water during mixing concrete, excessive amounts of it can create numerous problems. Excessive moisture is the result of free water in concrete, and moisture rising from the moist surrounding environment. Because of the special issues that may result into the failure of certain parts of structure, humidity control is an essential preventive and corrective measure which starts from its measurement. There are certain effects like increased PH level, decreased strength and microbial growth which usually originates from the high humidity problems.
Excessive moisture affects the concrete due to lack of climate control. The best preventive measure is to identify and correct humidity problems before the installation humidity measurement device.

After concrete cures, temporary humidity and temperature solutions will help mitigate moisture problems and its damaging effects.

In case of the bridge under consideration, cracking is the major problem. These cracks are the results of external environmental condition, humidity problems and the temperature changes. Humidity is a major concern in the case of this bridge because structure is situated on the waterbed where the external surface can be moist most of the time. The resulted problems because of this temperature and humidity issues can be easily visualized by the crack observed on the surface of sidewall during the crack analysis of bridge. On the basis of crack analysis it was summarized that "*Most of the cracks can be seen on the side walls of the bridge structure. There are only a small number of cracks on the top of the structure. There are a few cracks visible along the lower part of box-girder cross-section but there are no cracks between the side walls (main supports)"* whereas from the AxisVM model it is also evident that the major temperature intensity variations are along the side walls where physically cracks can be seen, therefore in this case author will recommend to use the temperature and humidity sensors together which will reduces the sensor installation costs and assembly problems as well. This installation is based on the intensity variation results of the axis model in which intensity variation is maximum at the joints of the sidewalls and top and bottom plates.

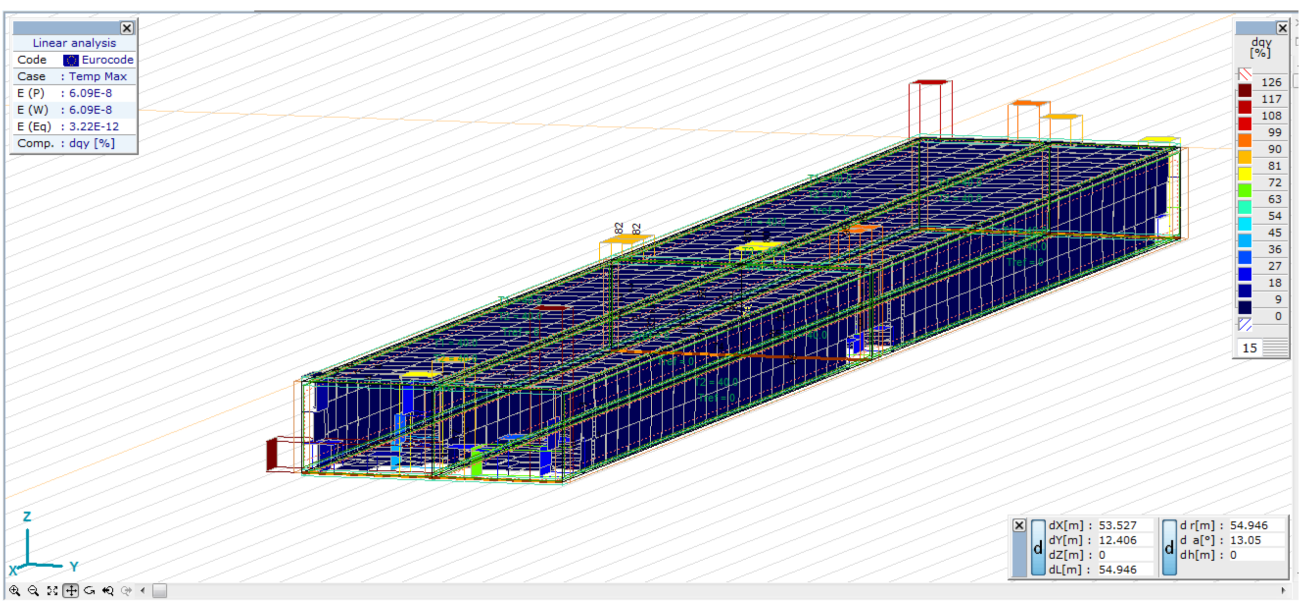


Figure 14- Temperature intensity profile of bridge

Joints are the most effective parts of the structure that can control cracking. Therefore, it will be recommended to install the sensors at to joints, as from the model examination it can be seen that maximum temperature intensity variations are also at the joints of sidewalls and plates. There are total 18 nodes along the each joint, so temperature and humidity sensors installation will be perfect at each of these nodes so total of 18 sensors are recommended. Same as strain sensors, temperature and humidity sensors are also installed along the reinforcement bars so the installation will be recommend along the rebar of maximum temperature intensity variation so that when concreting will be done for the renovation of structure temperature and humidity can be regularly measured. The modelled sensors locations are shown in figure 15.

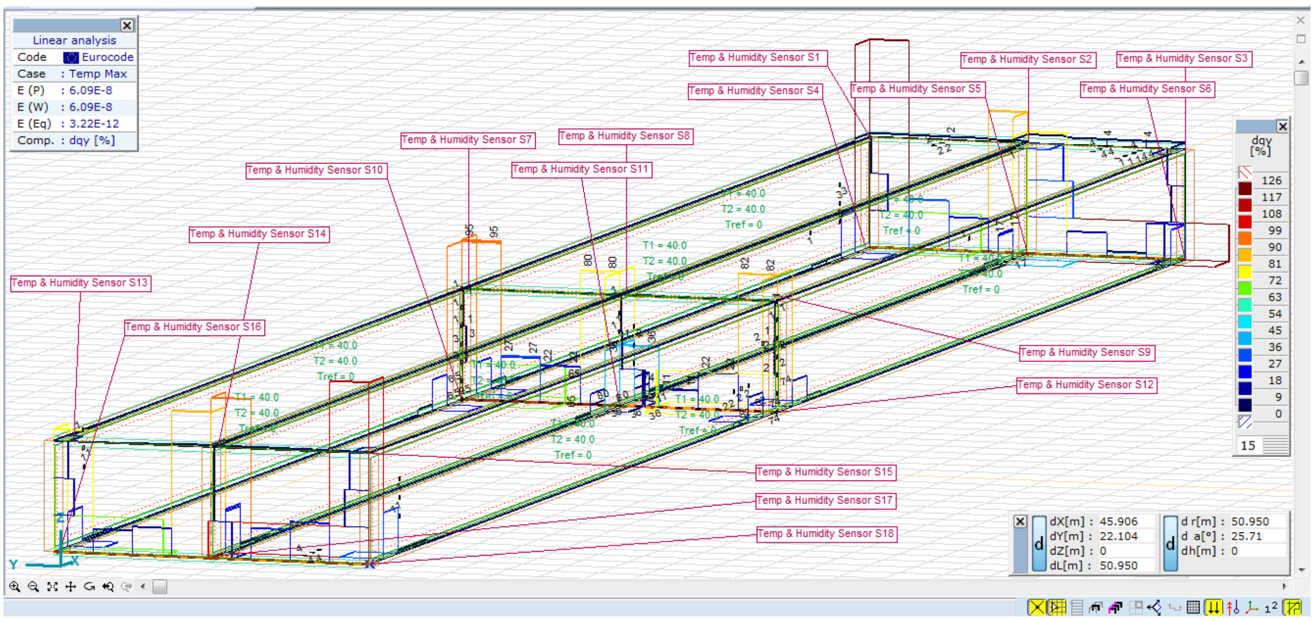


Figure 15- Locations of Temperature and Humidity Sensors

6.4 Installation of Weighing Sensors

Weighing sensors are the weight sensors which scene the weight of the passing object over it. These sensors covers certain area so in order to measure the weight over the whole surface area they needs to be installed at a specific place from where it can measure the weight over the whole span. Identification of location is based on the analysis of bridge span in order to find the location on the surface of bridge where surface stresses concentration is maximum because this will be the position where maximum stress can occur and if the sensor strip is installed at this location, it will be able to cover the whole span where the stress concentration will be less.

In order to identify the maximum stressed location over the surface of bridge, maximum load of truck 481 kN was taken into consideration and it was considered that the bridge is fully loaded with these trucks to apply the weight condition. In this way analysis is carried out under maximum load condition. Analysis results gives a particular location on the surface of bridge where the surface stress is maximum. The distance of this point is measured from the support which is measured to be 7.886 m from the right support. So at this location a channel according to the dimension of the sensor strip is cut into the roadway, where sensor is placed.

Figure 16- Example of Weighing Strip sensor

Special attention is given to channel as after the placement of sensor channel is filled with grout so that it does not disturb the traffic. So, on the basis of AxisVM model, one sensor in each span at the recommended location (shown in figure 17) is to be installed. In order to cover the whole bridge 5 weighing strip sensors are recommended.

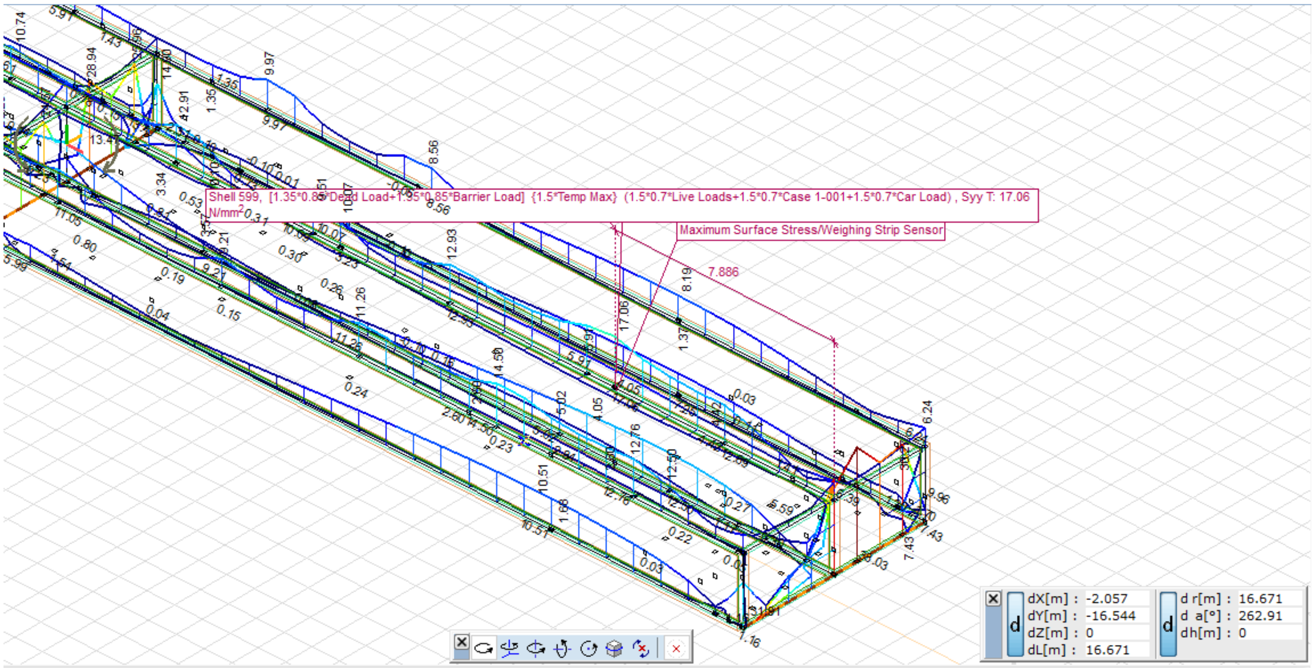


Figure 17- Location of Weighing Strip Sensor

6.5 SHM Model of the Bridge

Based on the above installations the final SHM system of the bridge is presented in figure 18.

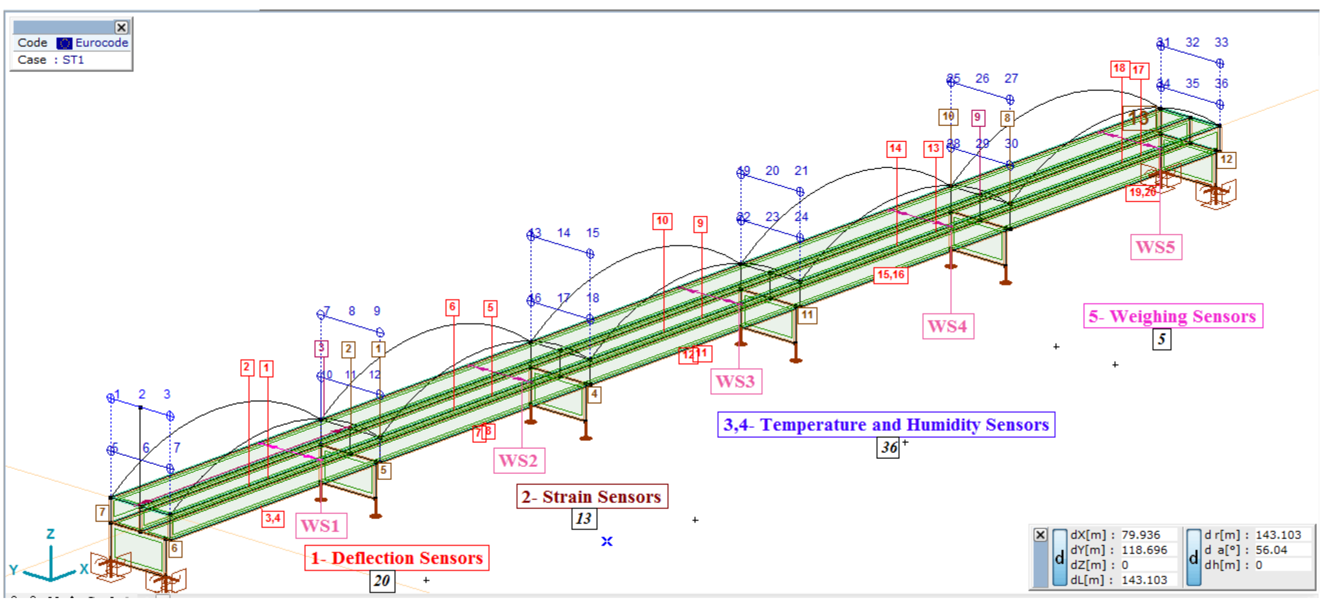


Figure 18- SHM Model with All Sensors

The model highlights deflection sensors in red colour, strain sensors in brown, temperature and humidity sensors in blue and weighing sensors in pink. These sensors are highlighted exactly at the same locations where they needs to be installed. For the whole length of bridge we need 20 deflection sensors, 13 strain sensors, 36 Temperature sensors, 36 Humidity sensors and 5 weight sensors. Total of 110 are recommend to be installed for complete SHM system of the bridge.

6.6 Warning System

Based on the data measured from the above mentioned system, measured data is passed through the several degrees of analytical sophistication. Each measurement is describing a particular physical parameter which in further describe the behaviour of the whole structure within its domain. These measuring units are supplemented with some alarming devices which are embedded with some predefined values of each parameter and when this value reaches or about to reach the level of sensitivity, a warning alarm is released to warn the concerned authorities. This system is very sophisticated so proper calibration and evaluation is needed by carrying out the trial tests periodically

CHAPTER 7

CHALLENGES AND FUTURE TRENDS

This research uses the software domain to develop the SHM system of bridge where the Technological advancements has also developed some Smart Bridge Inspection methods which can directly help to establish SHM of the structures. So, it is evident that many progresses have been archived in the area of SHM of Civil structures but still there are many questionable things in this system which are the main challenges. Although many studies were carried out to highlight these challenges [47, 48], which provides the future trends of SHM for civil structures but the field of SHM is developing rapidly, so visions should be up-to-date in time. Main challenges and future trends can be

- Damage detection is the base of SHM because obtaining an accurate data is important in a way to solve the problems related to the development of advanced sensors. The durability, stability, and reliability of sensors are of great important for the development of reliable SHM system.
- Damage should be identified accurately. It has certain challenges like environmental and operational variability, separating environmental variation from damage, errors in non-modal based damage detection, and Damage localization. All of these parameters can affect the stiffness and mass in a nonlinear manner and thus affect modal properties. Therefore, new science and technologies should be developed to solve the challenges,
- The development of smart materials technology require some high quality sensors which can be anticipated and can be utilized in SHM systems.
- Mobile technology should be integrated so that Wireless sensing technologies can be improved and frequency range and accuracy can be improved for the system.
- Some other challenges include long-term health assessment of structures and life-cycle ultimate capacity prediction.

Keeping in mind the above challenges it is concluded that SHM requires a sophisticated system including highly efficient data acquisition server, latest data storage technologies, proper data management system, data processing technologies, data analysis and modelling technologies, which probably were not the objective of this research work but the second phase of this research work is based on analysis of SHM in which author will analyze an existing structure over which

SHM system is fully functional. This extension of research work is in process on the basis of which new technologies, i.e., big data and cloud technologies, artificial intelligence, augmented reality integrated with Bridge information modelling (BrIM) are anticipated to be used to solve the issues of SHM.

After identification of certain damages associated to structure, author is also working on the strengthening of existing structure. Strengthening work, using the ATENA software, is in progress that can be presented on later stages of research work.

CHAPTER 8

SUMMARY

SHM is a key to modernize the Civil Engineering aspects related to renovation and rehabilitation of existing structures. In recent times, time and economy are the major constraints of the construction industry for which SHM is a helpful tool. SHM system has a lot many advantages but modelling of this system is a major concern because it involves a high degree of critical analysis of structures under consideration but once it's established, it given the proper monitoring and assessment of existing structures. Same can be seen in case of the Bridge, which was the subject of this research work. This bridge has been renovated a couple of times but after a few years same problems reappear. Therefore, it been considered that the proper monitoring of this bridge (as per the recommended SHM model) will highlights the main causes of the damages and will warn the concerned authorities for any renovation work if required. In this way not only the time, for long and cumbersome testing and analysis work, can be saved but the economy as well. This system is capable enough to make the structure technically sound, durable as per the aspects of sustainability of structures.

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