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MONITORING AND SAFETY OF HANDLING EQUIPMENT

Janusz JURASZEK
University of Bielsko-Biała

Abstract:
The paper presents a new solution for continuous measurement of deformations of the beam of travelling crane based on optical fibre Bragg gratings system. A verification of obtained results was done using resistive strain gauge method and magnetic metal memory method was used. Usage of the results of continuous measurements of deformation of the structure of the crane as actual boundary conditions in FEM numerical simulations was proposed in order to enable the analysis of the behaviour of whole structure.

Key words: *optical fibre Bragg grating sensors, overhead travelling crane, monitoring, operational safety, FEM*

INTRODUCTION

Overhead traveling crane is one of the most commonly used types of gantries in power plants, mining, where it is a necessary equipment to transport coal to a conveyor belt, delivering it to the furnace in the plant. The expected lifetime of the crane is usually 30 years. If this period is exceeded, it is crucial to ensure operational safety. The paper presents a solution for continuous measurement of deformations of selected beams of the crane bridge, and thus monitors the safety of its work. It is based on a system of optical fibre Bragg grating sensors. The place of installation of optic fibre sensors were chosen based on numerical simulations of the gantry beam, based on the finite element method. A verification of the obtained results was conducted with the method of resistive strain gauge and a new method of metal magnetic memory was used as well. Uncertainty had been determined using optical fibre sensors and resistive strain. The use of the results of continuous measurement of the deformation of the crane as the actual boundary conditions (in solving the reverse issues) was proposed in numerical simulations and FEM, for the analysis of the behaviour of the whole structure.

LITERATURE REVIEW

The introduction shows the development of fibre optic systems with Bragg'a grids and types of cranes and technical requirements.

The first works on the photosensitive fibres date back to the work of Hill 1978 [1]. However, the first practical application is in the works of Meltz [2] in 1989. The introduction of a full monitoring system using FBG sensors took place in 1999-2003 [3]. From this point rapid development of this method in a wide range of practical applications can be seen. Patric and co-authors in [6] demonstrated that the technology of fibre optic strain, temperature and pressure sensors, developed in recent years, is more effective with respect to conventional strain gauges. Guemes and co. [5] described the use of FBG sensors in composite materials in airborne electromagnetic noise conditions. Kamrujjaman Serker and Wu [2] used FBG sensors to monitor the durability of bridge structures – for structural health monitoring (SHM). FBG technique combined with multiplexing was implemented to monitor the blades of wind turbines in Japan (Eum and co. [3]). On-line monitoring of the temperature in the 400kV conduit line deflection has been successfully implemented in the system based on Bragg sensors (FBG). The complete system has been installed on the ACSR cable. This way, continuous surveillance of thermal and mechanical loads occurring in the supply line have been achieved. FBG sensors have also been used to monitor the intelligent design [3, 4], where they were characterized by high reliability, sensitivity, immunity to electromagnetic interference, small size and low weight. The analysis of the adhesive layer and the optical fibre sensors fastening strength parameters module layer on Kirchoff example has been shown in [4]. B. Ahmad, T. J Ali and A. R. Rahman have presented an analysis of changes in pressure in the tanks using FBG sensors [7]. K. Dragan on a Fourteenth Australian International Aerospace Congress pointed out the good correlation of FBG method with other methods of non-destructive damage detection on an example of the main rotor of a helicopter. It was also noted that the FBG sensors are fully accepted by specialists in the field of monitoring of large building, composite and air structures. The research of overhead cranes was also conducted by Ładecki and Badura, using conventional strain gauge sensors [8, 9].

A typical range of activities performed during acceptance testing for a crane are presented in the standards. The scope of the research includes samples:

- static (performed with a load equal to 125% of the nominal at the most unfavourable position of lifting mechanism, trial time – at least 10 minutes – unless longer time is required
- with a load lifted from the ground at a small height). No permanent deformation of the crane bridge and return to the state before loading are being checked);
- dynamic (performed after a successful result of a static test with a load equal to 110% of nominal with the execution of at least two cycles).

Static and dynamic tests rely on the initial position readout by means of a leveller or other measuring device (laser rangefinder). Then the load is raised to a value of 125% of a nominal load, the crane is left under load for 10 minutes, the deflection reading is made from the leveller. After that the load is lowered and reading is carried out using the leveller. Then the elastic and permanent deflection has to be specified. In the case of the dynamic test the load is limited to 110% of nominal load, some work movements using all the mechanisms are performed and the behaviour of the crane is observed. After performing this test random check on the supporting structure (in accessible locations) should be carried out - especially one should pay attention to connections.

The analysis of studies of cranes could show that all attempts very carefully check the condition of the crane. Unfortunately, this is not the case, because they can detect only larger damage and irregularities. It is a post factum action after the cracks or damage appears. The trials are not able to answer the question of whether there are construction crane areas of stress concentration which may cause cracks. The paper presents a new approach for conducting a priori diagnosis – indicating potentially dangerous areas in advance. It will be based on the method of optical fibre Bragg grating sensors.

CRANE DEFORMATION MONITORING USING OPTICAL FIBRE BRAGG GRATING SENSORS

Improving the safety of transport equipment, often special-purpose constructions, forces the implementation of new technologies, enabling the construction of highly accurate measurement systems, often with new, unique properties. The dynamic development of optoelectronic technology based on the propagation of light in an optical fibre contributed to the creation of modern sensors for strain measurement, such as: Bragg sensors (FBG called Fiber-BraggGratings), Fabry-Perot (F-P), Brillouin. Systems based on these modern sensors have several advantages that distinguish them from conventional strain gauges.

FBG sensor is obtained by the interaction of the core of single-mode fibre periodic pattern of intense ultraviolet light. The exposure causes a steady increase in the refractive index of the fibres' core, forming a solid modulation. Such modulation is formed on a single incision made inside the optical fibre. At each periodic refractive index change a small amount of light is reflected. Rays, reflected from each of the incisions are further interferential strengthened when the difference of paths of rays reflected from any of the two network planes parallel to each other, is equal to the integer multiple of the wavelength of the rays. This is determined by the Bragg condition and the wavelength at which the reflection occurs is called Bragg wave. The lengths of the light signals other than Bragg wavelength are not matched in the phase, and are therefore transparent.

A light beam with a broad spectrum inserted into optical fibre with the FBG passes through the optical fibre, apart from a narrow spectrum that is reflected from the Bragg grid at characteristic wavelength (Bragg wavelength) and is about 0.2 nm spectral width. The wavelength characterizes Bragg grate and is used in measuring systems. The characteristic wavelength is given by the following equation:

$$\lambda_B = 2 n_{eff} \Lambda \tag{1}$$

where:

λ_B – wavelength in a vacuum,
n_{eff} – refractive index, dependent on λ and the medium in which the light propagation occurs,
Λ – Bragg grating period.

Wavelength difference:

$$\Delta\lambda_B = s_\varepsilon \cdot \Delta\varepsilon + s_T \cdot \Delta T \tag{2}$$

$$s_\varepsilon = \lambda_B \left(1 - r_a\right) \tag{3}$$

$$s_T = \lambda_B \left(a + \xi\right) \tag{4}$$

$\Delta\varepsilon$ – change in stress,
ΔT – change in temperature,
s_ε – deformation value for a wavelength range of 1520 ÷ 1560 nm equal to 1.2 pm/με,
r_a – constant elongation,
s_T – temperature value for the wavelength range of 1520 ÷ 1560 nm equal to 1.2 pm/με,
a – linear temperature coefficient,
ζ – fixed temperature.

The equipment used for diagnosis of cranes includes:

- optical interrogator – Optoelectronic device for powering optical fibre system in the light, reading and changing the wavelength of signals, summing them up and transferring to the recorder
- optic fibre sensors with Bragg gratings – a section of optical fibre inside which Bragg grid has been applied, generating a change of the refractive index,
- temperature compensator – to compensate for the change in Bragg wavelength, when measurement is taken at temperatures other than 20°C,
- processing and analysing unit – it is usually connected to a recording software enabling observation of changes to the analysed values in real time.

TECHNICAL ANALYSIS OF THE TEST OBJECT

Two overhead traveling cranes located in two different countries were studied. One crane worked in the plant and was used to move coal from storage to the chute feeding boilers. In turn, the second one, allowed the transport of construction materials at a close range in a large construction company. Greater intensity of work occurred in case of an overhead crane located in the power plant. Both structures belong to the overhead traveling cranes. The crane working at the plant has undergone a modernization. Before conducting the research one should carefully read the technical documentation of cranes. A very important issue is to analyse any design changes made during the operation of the facility. Analysed carburizing crane at the power plant was built in 1980. It consists of two 13-span sets composed of plate girder gantry beams supported on pillars of truss construction. The length of a span is about 12 m – Fig. 1.

The width of the crane is 32.01 m, and the height of the overpass from the upper spread footings to the top of the foot of the gantry beam is 8.37 m. Originally gantry beams were designed as I-joists plate girders with a height of 824 mm. The centre plate is made of metal with a width of 800 mm and 10 mm thick, and strips are made from sheets of a width of 250 mm and a thickness of 12 mm – Fig. 2. This supports four-branch trusses with a 800x600 mm spacing. Branches were taken from 160x160x15 angle irons, made of 75x75x9 angle irons and 45x45x5 angle irons. Crane track is made of rails S42 welded directly to the upper belts of gantry beams. Overpass bridge was designed of Wema type grates. The initial design of the overpass has been modified in subsequent years [6], reinforced due to the occurrence of relatively large displacements Fig. 3.

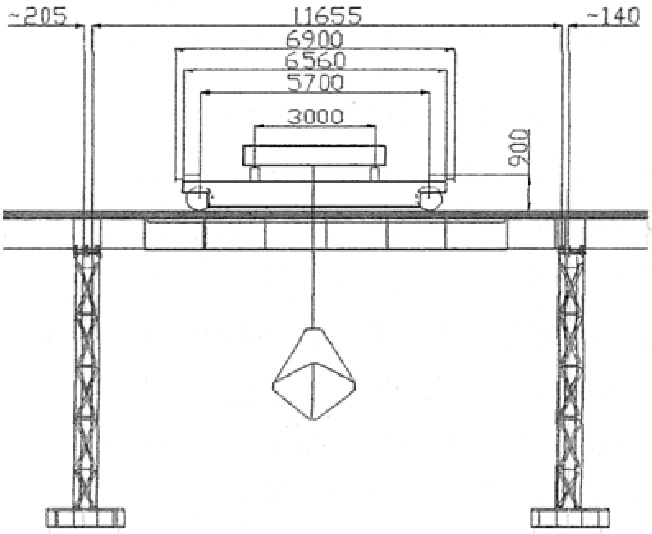

Fig. 1 Diagram of the overhead travelling crane

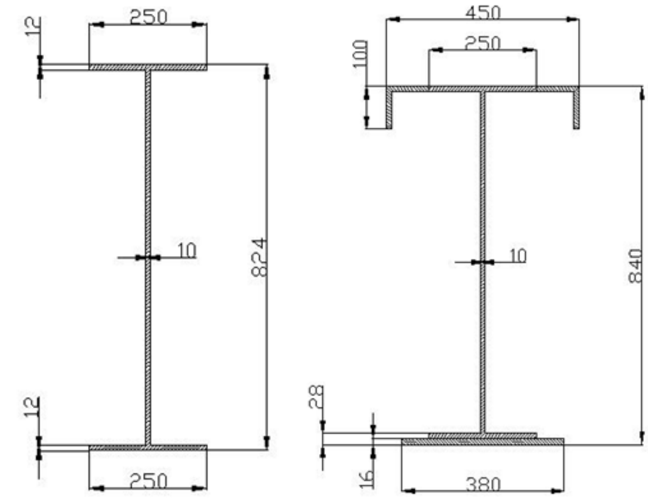

Fig. 2 A cross section of I-beam 820, before and after modernization

Strengthening has been subjected to:

- gantry beams' upper belts, to which in the central section of 9m length, two iron angles has been welded (depending on the span: 100x100x10 or 100x100x12),

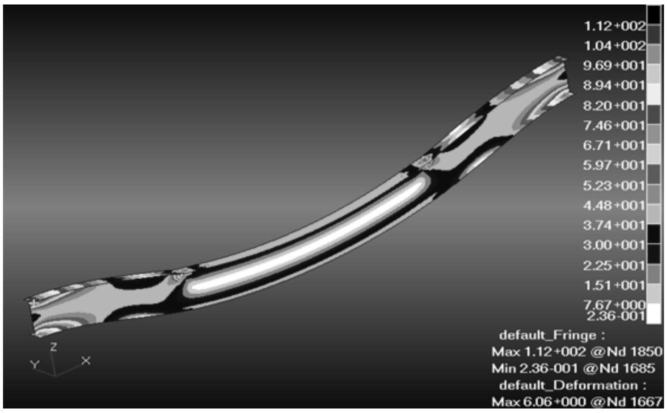

Fig. 3 Reduced stress distribution in the gantry beam according to Huber hypothesis

- gantry beams' lower belts, to which the central sections of 9m length overlay sheet (380x16), increasing height of the beam to 840 mm, has been welded,
- to the branch poles four additional angle irons has been welded (160x160x15).

The following has changed:

- pillars has been anchored in the foundation by introducing increased bolts spacing and additional steel grates anchored to the base lattice poles. Bases for foundation have also been expanded.

The following have been made on the basis of expert assessment, conducted in 1996:

- two braces of the channel section 120 were added between the beam ribs and the head of the supports, to reduce the horizontal displacement of the of the gantry beam,
- crane rails have been replaced to rail type S49,
- flexible rails mounting, type Gantrex 9000, have been used
- thorough anti- corrosion restoration of the following coatings have been done: gantry beams', brake bracings', and supporting them from the outside – track vertical trusses.

The modernization of the crane that was carried; consisted in welding an additional belt at a 9 m length to the belt of the lower I-beam; thus it has not been welded on the entire length of the gantry beam which length is 11.655 m.

The transverse dimension of the welded shelf is 380 mm and is larger than the bottom shelf of the I-beam, which is 250 mm. Additional reinforcement placement is shown in Fig. 2.

OVERHEAD TRAVELING CRANE DEFORMABILITY RESEARCH

The key issue is the appropriate choice of spots on the gantry beam, where deformations measurement will be carried out. These places are determined by technical and economic constraints. Technical limitations indicate the possibility of measuring the deformation of the bottom flange of the gantry beam, because the upper belt is installed and running rail communication system. In turn, economic constraints limit the number of optic fibre sensors to a minimum. Here one can follow the experience of the experimenter or perform numerical simulations aimed to identify most strenuous spots. Experience shows two areas. The first one is the place of occurrence of the highest value of the bending moment and deflection in the mid-length of the beam. The second place is the reinforcing weld overlay of a 380 mm width to 9000 mm in length at its ends, perpendicular to the beam axis . These areas were also verified by numerical simulations. A numerical 3D model of the analysed gantry beam has been built, based on the finite element method codes, taking into account the modernization and detected shift in the axis of the span compared to half the distance between the truss poles (Fig. 3). The results of numerical simulations confirmed the previously identified two areas, i.e. the area in the middle of the span and weld overlay reinforcement places. The level of stress in the analysed areas was also determined. The tension in the middle of the span is about 40 MPa.

Based on the above analysis, it was decided to place the optic fibre sensors in the middle of the length of the beam (cross-section IV sensor # 2.3) and at the end of the reinforcing plates (cross section VI sensor 1). The location of optic fibre sensors is shown in Fig. 4.

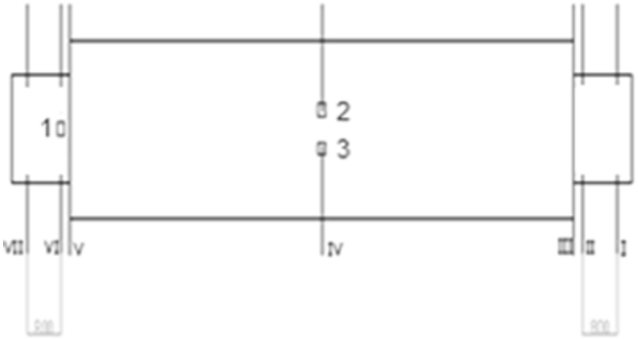

Fig. 4 The location of optical fibre Bragg grating sensors on the bottom of the gantry beam

In addition, half the length of the beam two different types of optic fibre sensors was applied, in order to control obtained deformation values, as well as evaluate the ease of installation of various types of optical fibre sensors. In the selected measuring points optic fibre temperature sensors were also introduced. They enable continuous temperature measurement, as well as compensation for its amendment. Both quasi- static and dynamic studies were conducted during crane trolley movement, loading and unloading of coal. Diagrams of the crane load are shown in Fig. 5.

The first diagram shows a fourfold passage of crane trolley. The passage may be full or empty skip. Next load cases illustrate the process of scooping coal into the crane skip and its dumping. It has been considered for five positions of the crane trolley I, II - III, V-VI, VII, specified by the location of the left wheel of crane trolley, the central position – IV, and similarly – five positions of the right wheel of crane trolley VII, VI - V, III - II, I. For the central position hysteresis and measurement uncertainty had been determined. The results of continuous measurements of deformation could be recorded at a frequency of 2000 Hz, however, practically for this type of measurements a frequency not exceeding 100 Hz proved to be sufficient enough. They are presented in the form of a report containing the particular wavelength for each of the of 1533 nm, 1551, and 1558 nm fibres, and changes in individual wavelength change of Bragg sensors

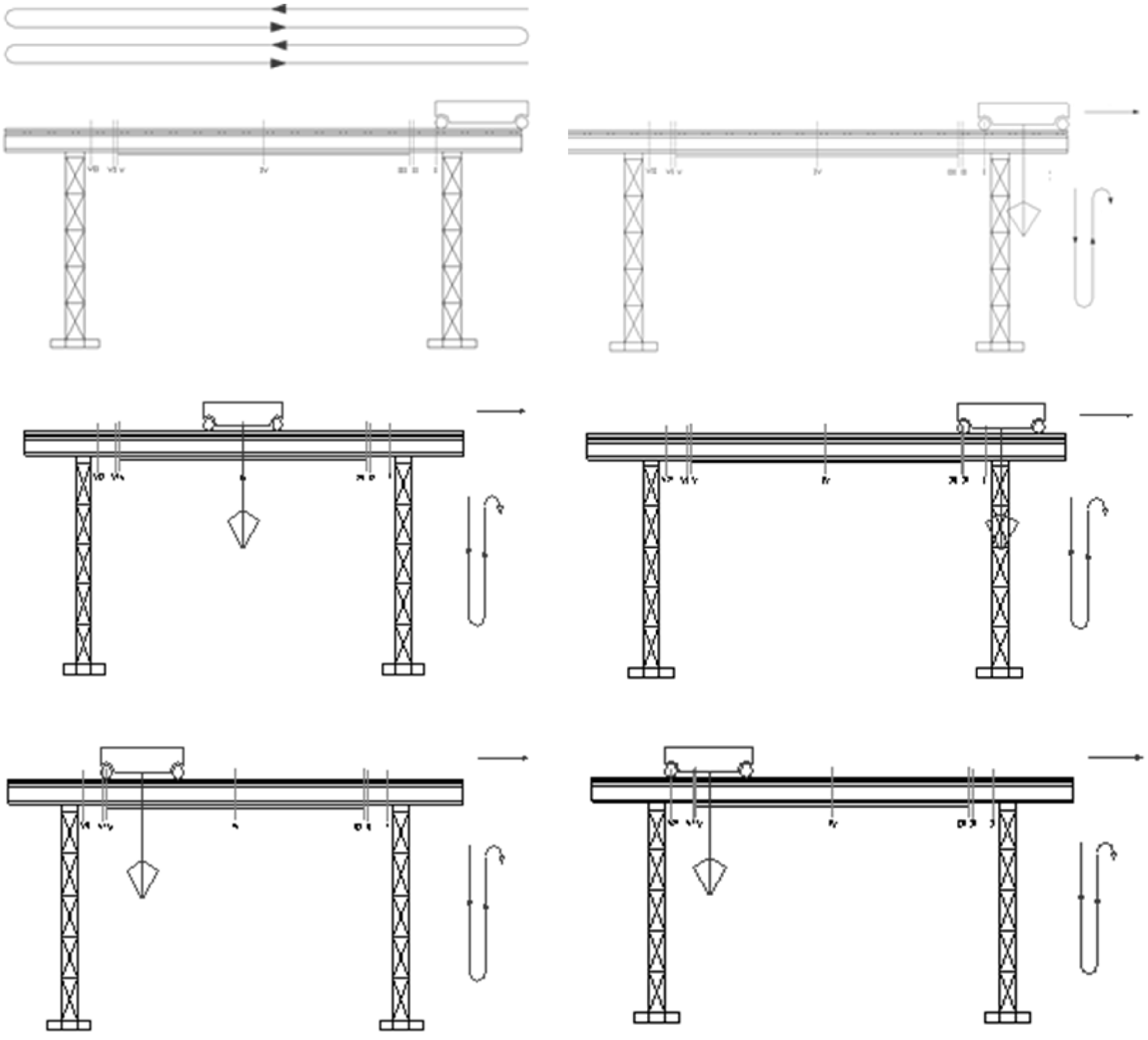

Fig. 5 Variants and configurations of the gantry beam load

under load. The software calculates the wavelength change of strain (strain 1-1, strain 1-2) for a fibre glued half the length of the gantry beam, as well as the fibre applied near the support gantry. Deformations are given in µstrain – 1/1000000. The deformation of the sensor mounted in the middle of the gantry beam reaches about 150 µstrain (Fig. 4, 5), while near the support – about 40 µstrain. Based on experimentally determined values of the actual deformations, it is possible to calculate on the physical relations basis, the components of the stress state in the fibre axis direction.

The recording system has a software that allows visualization of the deformations' results. Sample diagrams of analysed changes in the size of the gantry beam are shown in the graphs below for different load configurations including:

- gantry passage with full load at maximum speed Fig. 6,
- deformation of the gantry beam with a full load and with an empty skip (no carbon), Fig. 7,
- deformation of the gantry beam with a full load, four times, Fig. 8,
- stress in the gantry beam during lifting and lowering, Fig. 9.

The stresses recorded during the trials of dynamic transit/with the greatest possible speed amounted at half length of the span about 43 MPa, while for the fibre optic sensor located near the support – 10.1 MPa. The graph also shows the repeatability of the process for the return transit of the gantry. The ratio of the stress in central part of the crane to the strain at the crane support is 4,3. The level of deformation of the crane during transit with full and empty skip has been studied (Fig. 7). For the transit with full skip, the deformations in the central part of the gantry beam are 195-210 µstrain, while for the transit with an empty skip – 175-182 µstrain. Thus, the deformation difference between transits with full and empty skip is 20-28 µstrain. It follows that the deformation of the crane, in large measure, is determined by the weight of the construction of the crane. One must therefore strive to reduce the weight of the crane construction. First peak marked by the arrow in Fig. 6, refers to the passage of the first wheel above fibre optic sensor, and the other one, to passage of the second wheel over the sensor. This is due to the so-called impact line.

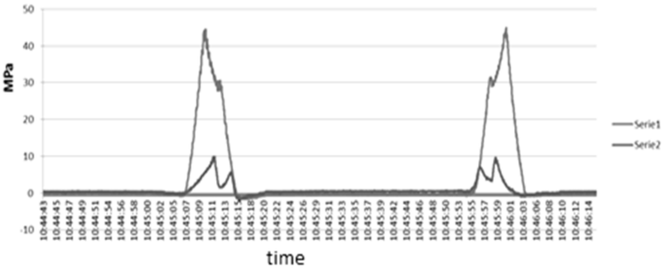

Fig. 6 Stresses in the gantry beam for gantry passage with full load - dynamic test

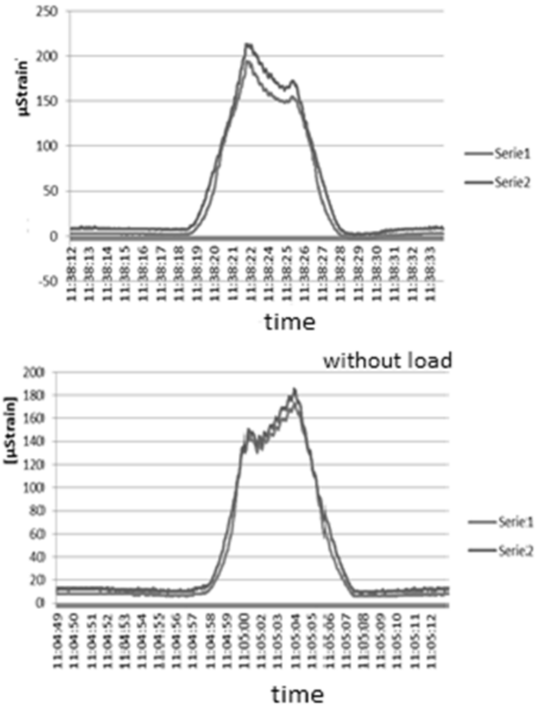

Fig. 7 Deformations of the gantry beam for transit with carbon load and without it

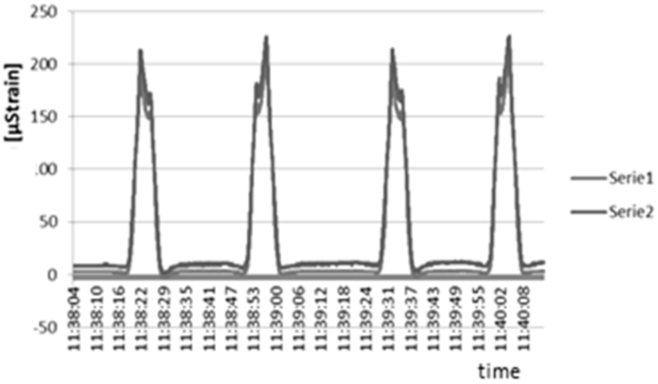

Fig. 8 Deformations for four transits of the gantry with full load

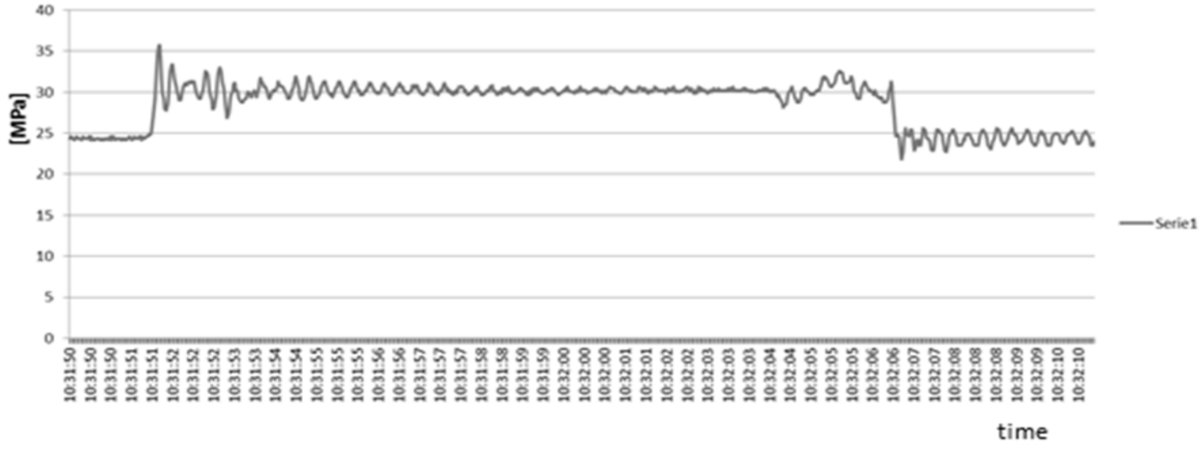

Fig. 9 Stresses in the gantry beam during cargo lifting and lowering

Studies on scooping coal into skip bucket and then its dynamic lifting and emptying (Fig. 9) are very interesting. The study was conducted for the five positions of the left wheel of crane trolley and the corresponding positions of the right wheel. The highest stresses occur in the central part of the beam. Raising the skip bucket creates vibrations. The number of cycles is about 30. A similar situation occurs during dumping. These are fading vibrations, which are not included in the standard overhead cranes' calculations. Even service life calculations do not take this important phenomenon into account.

The studies conducted using fibre optic sensors have enabled the appointment of the actual state of deformations in the construction of the crane, used for carburizing at the power plant, and the appointment of a dynamic factor. The largest value for the dynamic factor of the analysed crane construction is 1.59.

Modernization of the gantry beam consisting of welded reinforcing strip – only 9m in length – that is not the entire length of the gantry beam is not optimal.

This modernization has significantly changed the stress distribution in the gantry beam, and introduced additional stresses at the intersection of the reinforcing strip with lower part of the gantry beam. Strain measurement uncertainty using fibre optic sensors for static tests was designated (Fig. 10). The term "uncertainty" is understood to be the biggest difference of deformation for the same load between successive processes of loading or unloading the crane. A biggest difference in the deformation process occurring between loading and unloading was adopted as hysteresis.

Uncertainty of measurement for fibre optic testing did not exceed 1.3% of the highest strain.

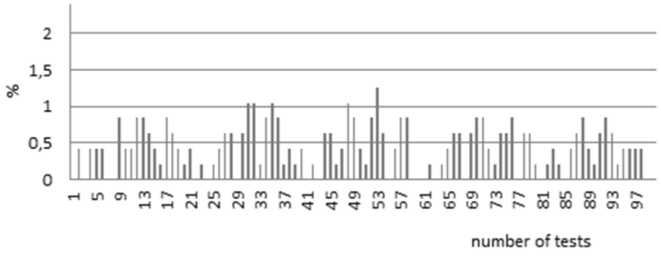

Fig. 10 Uncertainty strain measurement using a fibre optic system

EXPERIMENTAL VERIFICATION USING RESISTANCE STRAIN GAUGE METHOD

Strain test results obtained using optical fibre Bragg grating sensors method have been validated using a resistive strain gauge method [6]. Strain gauges were glued to the gantry beam in the middle of its length and near the supports in the same position as optic fibre sensors. Bridging fields system with temperature compensation has been used. The results were recorded using a computer system. Both static tests, involving gantry overloading in certain sections of the rated load and dynamic tests involving the invasion of gantry with the greatest possible speed on the analysed gantry beam were carried out. The values of stress for the middle position of the load causing the greatest value of the bending moment for the various beam cross-sections are in the range of 16 to 48 MPa.

The results of the gantry beam deformability tests in the dynamic fourfold gantry transit through the beam is shown in Figure 11. This test was carried out analogically to the measurement test with fibre optic sensors Figure 8. Strain values obtained in both assays are at a level of 230 µstrain, which means normal stress with a value of about 48MPa. The study confirmed the strain gauges obtained using optic fibre sensors. Scooping and dumping process are shown in Figures 12 and 13 where vibrations caused by the process are visible.

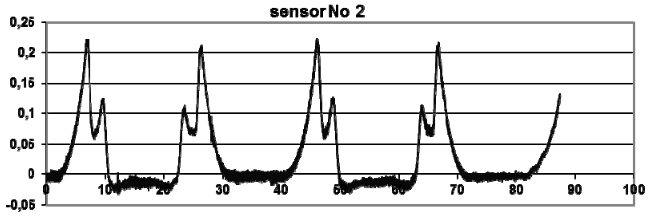

Fig. 11 Deformations from strain gauge measurements for 4-fold gantry trolley passage

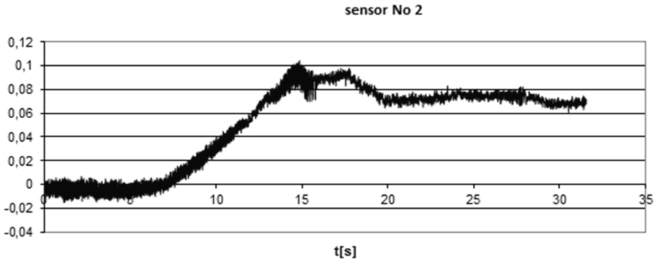

Fig. 12 Deformation of the beam while scooping coal into the skip

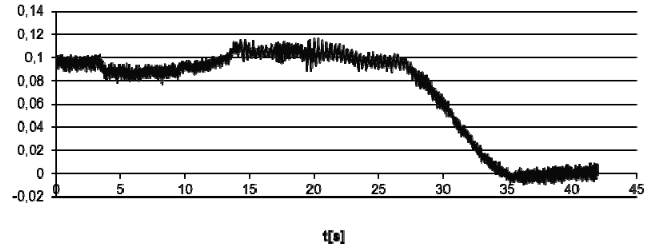

Fig. 13 Deformation of the beam when pouring the coal down the chute

The increase in deformation of the gantry beam while scooping and dumping of coal is about 0.11 per mille which corresponds to stresses growth of about 10 MPa. It should be noted that the measurement system was zeroed before taking the coal to the skip. Figure 14 presents 10 superposed carbon scooping processes. During dynamic load lifting, considerable load vibrations occur.

Fig. 14 Types of fibre optic sensors

Beam strains determined by two independent experimental methods are practically the same and amount to 0.12. This applies to both static and dynamic transit tests. In case of dynamic load lifting, due to the varying length of the holding rope, these values vary in the range of 10%.

An analysis of the ease of attaching different types of optic fibre optic sensors has also been made. The sensor shown in Figure 14 takes measurements on a relatively small measurement basis but it is very sensitive to mechanical damage. In addition, the sensor must be properly tensioned so as to record the deformation throughout its intended range of strain. Tensioning process is complicated because it requires the initial connection with the interrogator and capturing measurement basis in such tension. Special handles for ensuring the proper tension were designed. The sensor pad mounted on a special mounting is easier to attach to the "ceiling", and more resistant to mechanical damage. On the basis of static and dynamic tests the stress values obtained using the method of optical fibre Bragg gratings and resistive strain gauge method were compared. In both cases the greatest stress of 60 MPa was achieved. The method based on optical fibres has a very important advantage of not having to build special compensation systems. An additional advantage is powering the fibre with light.

DETERMINATION OF AREAS OF STRESS CONCENTRATION USING METAL MAGNETIC MEMORY METHOD

Studies of the crane beam was carried out in order to identify areas of stress concentration in the beam as well as assessing the impact of operating time on its image by the method of magnetic metal magnetic memory. They consisted of scanning the lower surface of the gantry beam both new - the reference beam, and the beam which has been operated for 30 years, and the appointment of the tangent and normal components of the scattered magnetic field and their distributions. New beam (Fig. 15) has a relatively small value of the level of normal component of the magnetic field strength of about 50 A/m and the gradient of the normal component level 5 A/m/mm. The beam which has been used for a period of 30 years is characterized by significantly higher levels of the normal component of about 200 A/m, which is four times more than in case of the new beam (Fig. 16). Furthermore, the gradient of the tangential component reaches a value 42 A/m/mm and is eight times higher in respect to the new beam. At this point the beam damage was identified.

The research of gantry beam using the method of metal magnetic memory allows one to define areas of stress concentration, damage not detectable by any other available method [3]. It is also an important opportunity to identify hazardous locations, a priori, i.e. before the onset of the first micro cracks. This allows one to take appropriate preventive actions.

THE CONCEPT OF A MODERN SYSTEM OF ANALYSIS

The concept of modern structural analysis system is shown in Figure 17. It consists of seven parts. Stage I includes an analysis of the technical documentation requirements, the types of materials used.

In a further step the relevant legislation should be reviewed, relevant standards appropriate for the analysed structure. A new solution proposed is to scan the structure using the method of metal magnetic memory and connect it to a computer simulations using finite element method. This method is in contrast to several others, and allows an a priori designation of the effective regions of stress concentrations. Then a thorough analysis of the selection of areas which will be covered by monitoring deformations is carried out. The monitoring will be done by means of optical fibre strain sensors with Bragg gratings. Information about the actual deformation will be directed to the numerical simulation system that will analyse the behaviour of the whole structure. It may turn out that it will be necessary to supplement the measurement system with additional sensors. Conducted analysis will make it possible to make the optimal decision concerning the admissibility of construction to operation. It is also possible to take modernization actions.

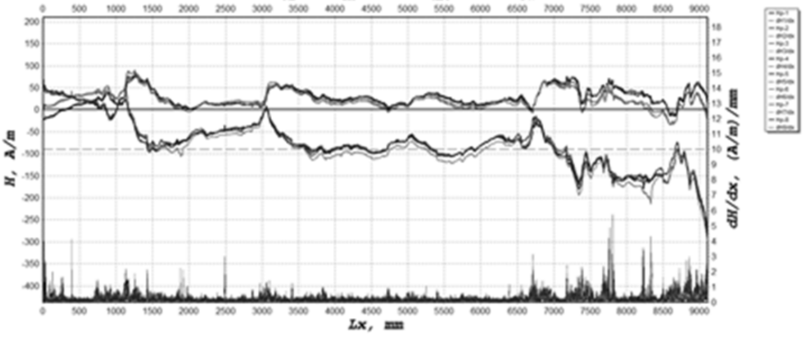

Fig. 15 Magneto gram for the new beam

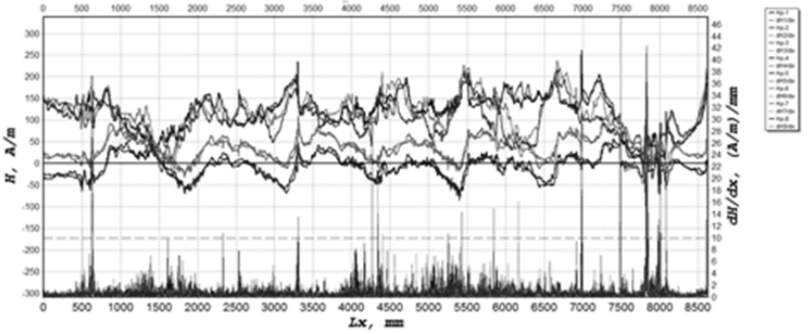

Fig. 16 Magneto gram for the beam which has been used for 30 years

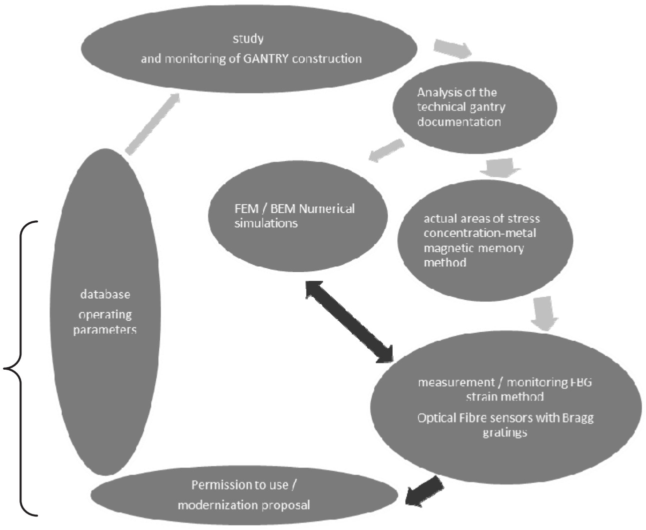

Fig. 17 Modern gantry analysis

After their completion, one should repeat the admission algorithm. The results of research and analysis should be collected on a regular basis in a relational database .It should also be pointed out that the proposed system can significantly contribute to increasing the operational safety of the structure. The introduction of two independent methods of the analysis of the correct operation of the structure greatly increases the probability of correctly locating a defect, damage or dangerous places that do not yet show any signs of damage. This is therefore a significant improvement over the currently used individual methods.

CONCLUSIONS

The paper presents the concept of monitoring and analysis of security of handling equipment. Conducting of deformability monitoring using optic fibre sensors with Bragg gratings was proposed. Deformation and stresses occurring in the gantry beam for different configurations of the crane load were determined. The highest stress values for the dynamic tests did not exceed 60 MPa. Validation studies were also performed using the resistive strain gauge method. Practically the same values of stress and strain were received. Comparing both methods, one can conclude that the optical fibre sensors with Bragg gratings method are more accurate and more convenient from a practical point of view. Strain gauges can be applied to the analysis of areas of less than 10 – 8 mm . The uncertainty of measurement using optical fibre sensors was also designated. It did not exceed 1.3%. Positioning of sensors and strain gauges was chosen based on FEM numerical simulation. Structure monitoring using the method of metal magnetic memory was proposed in order to identify areas of stress concentration. The results should be stored in a relational database. The components were linked together to form a crane analysis system.

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prof. univ. dr hab. inż. Janusz Juraszek
University of Bielsko-Biała
Head of Civil Engineering Department, POLAND
email: jjuraszek@ath.bielsko.pl

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