Comments on Structural Condition Analysis Based on Strain Measurements on Tripod Model

Szymon Opoka, Magdalena Mieloszyk, Szymon Derra, Wieslaw Ostachowicz

COMMENTS ON STRUCTURAL CONDITION ANALYSIS BASED ON STRAIN MEASUREMENTS ON TRIPOD MODEL

S. Opoka[1], **M. Mieloszyk**[1], **S. Derra**[1], **W. Ostachowicz**[1,2]

[1] *Polish Academy of Sciences, Institute of Fluid-Flow Machinery, Fiszera 14, 80-231 Gdansk, Poland*
[2] *Warsaw University of Technology, Faculty of Automotive and Construction Machinery, Narbutta 84, 02-524 Warsaw, Poland*

szop@imp.gda.pl

ABSTRACT

Selected strain measurements performed on tripod model are described in this paper. Two problems are investigated here. First, the influence of bonding procedure and surface's curvature on initial strain in optical sensor is shown. It seems that initial strains due to bonding procedure and curvature can be respectively high in comparison with allowed strain range of the optical sensors. Second, the ability of strain sensors to indicate changes in boundary condition in one leg of the tripod is also shown. For tripod model changes in boundary conditions can be detected by sensors not necessarily located at the bottom part of the structure. Maximal shear strain can be valuable indicator of such changes.

KEYWORDS : *offshore support structure, wind turbine, tripod, strain, damage detection*

INTRODUCTION

Future wind energy farms will be built in deeper locations on the sea because of lack of space in the shore proximity, aesthetic reasons and better steady wind conditions. According to [1], the most of planned wind farms fixed to the seabed will be located at a maximum depth of 50 m. Bigger size wind turbines are now designed in order to produce more electrical power than the ones already in use. At the same time the more severe sea conditions force designers to find out reliable bigger support structures which can sustain their increased self-weight and operational loads. The main activities in this subject are devoted to design of the entire structure, electric assembly and monitoring of electric properties of the generator in order to produce electric energy of sufficient quality. On the other hand the problems connected with structural health monitoring (SHM) of offshore wind turbines have relatively short history.

There are different definitions of support structure for wind turbine. In this paper the support structure means underwater part of the wind turbine which stands on the seabed and is directly connected to the transition piece cylinder. The most common support structures are: monopile, tripod, jacket and gravity based structure. The simplest one is the monopile (single cylinder), but in order to use it in deeper waters large diameter cylinder must be used in order to resist lateral loads [2]. The gravity based structure is very heavy concrete structure which stands on the seabed significantly lowering the center of gravity of entire wind turbine structure. This solution is prone to the instability in foundation conditions. The more robust solution is represented by the jacket-type structure. These spatial frame/truss lattices proved its usefulness in offshore industry where they served as support for jacket platforms or as the skeletal legs of jack-ups. The main obstacle of the jacket solution is high demand for production workload which together with the number of the wind turbines in the farm causes high overall production cost. The intermediate solution between monopile (simple but inefficient in transferring lateral loads in deeper waters) and jacket (complicated but efficient in transferring loads due to larger base) is tripod structure. The tripod structure is composed of main vertical tube to which three brace members with pile guides are connected. The example of the tripod structure is described in the next section.

The wind turbines are recognized as ”fatigue critical machines” which means that the fatigue problem is one of the most important parameters in design process, especially for turbine blades. In [3] the theory, load spectra and material properties in context of fatigue are described. In [4] a radial arrangement of strain sensors around the bottom part of the tower near the base weld joint was used for crack detection. It was found that the strain difference between adjacent strain sensors performed well as the fatigue crack indicator. The successive analysis was based on the fact that the crack perturbs local strain field. Additionally, it was found that fluctuating strains are more important for some damage detection applications because they might prevail the static strains. More expanded sensing system was proposed in [5], where several accelerometers, two inclinometers and strain gages will be used in instrumentation plan of HiPRwind floater. Design of support structures for wind turbines can be found in [6] where the effect of the aerodynamic damping of the operating turbine on support structure dynamics and the fatigue problems based on analysis of signals in frequency domain are described. The codes for design of wind turbines can be found, for example in [7].

Loads which occur from the weight of rotor, nacelle and tower of the offshore wind turbine and the environment must be safely transferred to the seabed by the support structure. Vibrations experienced by the support structure are imposed on large mean value (static stress from the weight of the entire structure) and can be interpreted as small perturbations about mean value [8,9]. Additionally, due to interpretation problems of the results for strains measured in different days continuous strain monitoring is suggested to reveal any transient phenomena which can be linked with some damage occurrence [8].

In literature, the strain sensors are generally used to monitor lower part of the tower which is generally above the sea level and top access platform of the transition piece. In contrast, our investigations tend to develop monitoring system for entire support structure submerged into the water. The system composed of Fibre Bragg Grating (FBG) strain sensors is capable to monitor submerged structures because the information is carried through propagating light in the optical fibre not by the electric signal. In recent decade, the strain sensing based on FBG sensors become mature technology. Now it is capable to measure strains not only in laboratory conditions but also in real ex-areas. For example, in marine environment FBG strain sensors were used to monitor the mast of sail training ship [10].

In next section stain measurements on tripod model are described. In Section 2 the influence of bonding procedure and the curvature of the tubes on the initial strain change in the sensor itself are described. Additionally, the sensitivity of strain sensors to changes in support conditions is revealed. Finally, some conclusions are formulated which are based on the presented results.

1. Strain measurements on the tripod model

The investigated model has been assembled from aluminium tubes welded together in order to form tripod structure, see Figure 1. It has been composed of main vertical tube called tower structure (TS), three upper braces (UB), three lower braces (LB), and three short-length cylinders at the bottom of the structure which serve as pile guides (PG) in full-scale structure. Each PG has additional ring with holes for fixation to the base. The thickness of the tubes is 3 mm. In one of the UBs the flange has been mounted. The flange has been composed of two rings welded to the corresponding tubes with round plate which has boltholes but no center hole. This assembly has been connected together with 30 Nm torque imposed on bolts. The tripod with bolted flange has been considered as undamaged structure.

On the tripod structure 39 FBG strain sensors have been installed (15 Micron Optic os3120 sensors with metal carriers and 8 HBM optical rosettes with sensors embedded into the plastic cover), see sensor’s locations on the model in Figure 2. One additional Micron Optic os4100 sensor has been used for compensation of the thermal output in readings from strain sensors. The sensors have been attached using two-part epoxy glue in order to assure good quality bond when the structure also will be submerged into the water in future investigations. Each single FBG sensor has been glued along

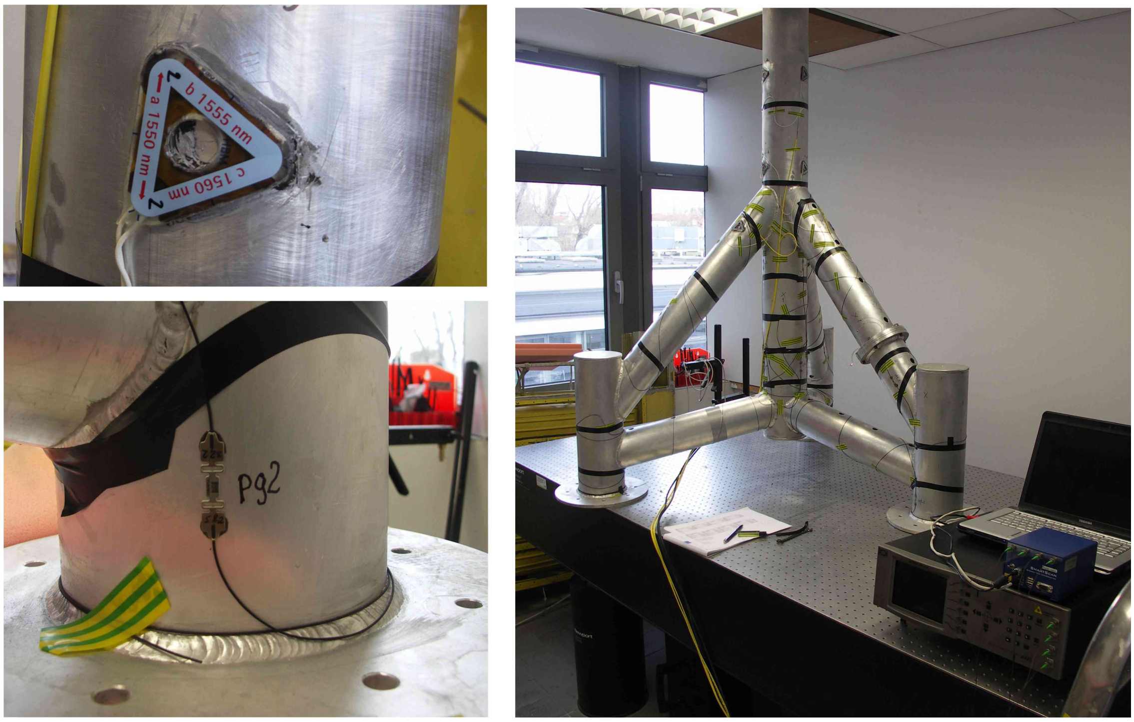

Figure 1 : The photograph of tripod model standing on the antishaker table together with two photos of single sensor (Micron Optic os3120) and optical rosette (HBM) used in experiments.

the generatrix of the corresponding tube. For strain rosettes the gluing procedure was cumbersome to some extent. Strain rosettes must have been initially bent in order to adjust to the curvature along the circumferential direction of the tubes. Therefore, the press pad was used to apply the pressure to the rosette firmly and evenly for approximately 5 minutes with the help of power tape and installer's hands. The sensors on the braces have been located at some distance from the holes in order to diminish the influence of the stress concentration around holes on strain readings (these holes have been made on braces in order to fill the interior parts of braces with water when the structure will be submerged into the basin). During measurements two interrogators Micron Optic si425 (for single sensors) and FiberSensing SmartScan (for rosettes) were used for data acquisition. For the results shown here the sampling frequency was set to 250 Hz.

The considered different states of the model are defined by: a) normal and damage state - the flange on the UB completely dismantled with round plate removed from flange, b) different boundary conditions - PGs directly fixed to the table by the bolts or PGs put on foams and fixed to the table by the bolts, c) different vertical loads - masses put on the top of the tripod. The case a) was motivated by the Alexander L. Kielland disaster [11], where the crack in circumferential direction of the tube was the cause of the collapse of the offshore platform. The case b) was considered because different seabed conditions are expected in different areas of the Baltic Sea. The case c) resembled the fact of changing mass of offshore platform due to oil storage where the production platform has tripod as the support structure. Here, only selected results for case b) are presented.

2. RESULTS

2.1 Initial strains in sensors and rosettes due to bonding procedure and curvature of the tubes

The properly designed SHM procedures should first monitor the behavior of the sensors and then the entire structure. Contrary to established techniques for electric strain gages [12], where the measure-

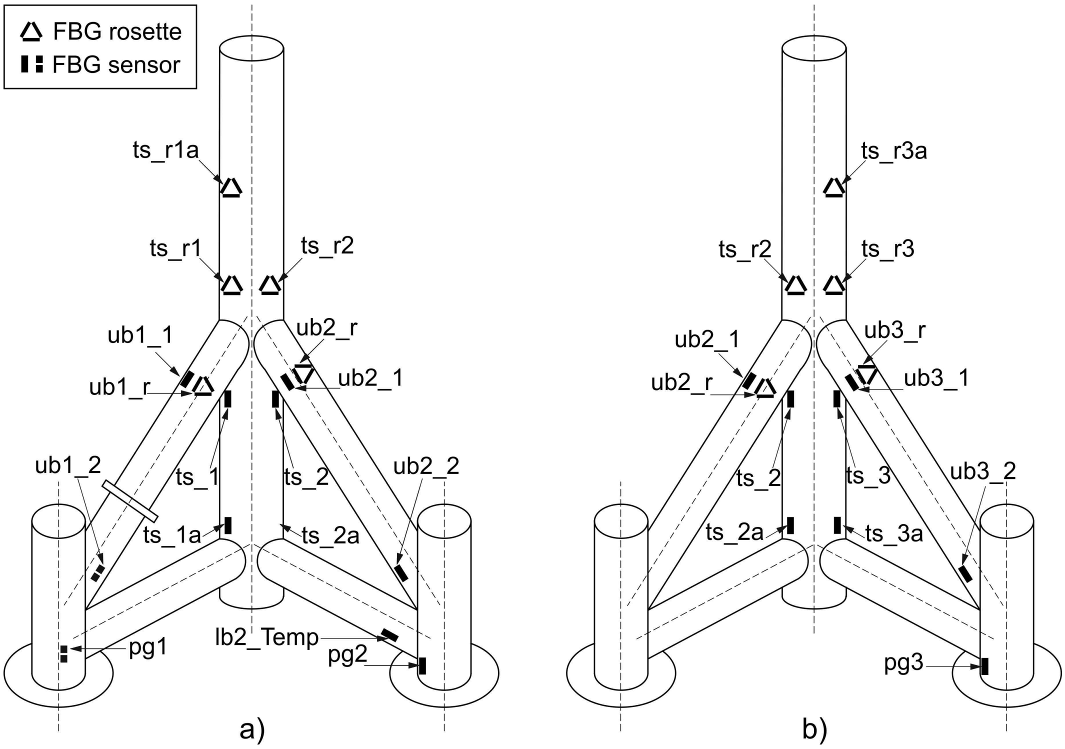

Figure 2 : The location of single strain sensors and rosettes on the model when only legs 1 and 2 are visible (a) and when only legs 2 and 3 are visible (b). FBG sensors are denoted by bars where solid (dash) bar denotes FBG sensor which is visible (not visible) from actual view.

ment is usually performed after the installation of the strain gages on the structural surface, FBG strain measurements allow to interrogate the condition of strain sensor before, during and after bonding procedure. This possibility allows to observe changes imposed on sensor and to assess about initial strain in the optical fiber.

The strain traces for os3120 sensors with metal carriers representing the state before, during and after bonding activities are shown in Figure 3. Big change in strains is observed for ts_1a and ts_2a sensors with values 400 and 280 $\mu m/m$, respectively. For remaining sensors the step change, if any, was relatively small. This final strain should be taken into account in cases where big strain changes are expected in the measurements. For os3120 sensor strain limit is ± 2000 $\mu m/m$. Therefore for ts_1a allowable strains are redefined to be in the interval $(-2400, 1600)$ if the value 400 $\mu m/m$ is considered as new reference zero point. Additionally, this strain shift can cause misleading interpretations of the results for densely deployed sensors in one channel for finite range of interrogated wavelengths (overlapping of the reflected spectra from neighboring sensors).

The possibility of strain step change for FBG sensors is important characteristic of these sensors where the initial straining in metal carrier influences not only the underlying structure but also the optical fiber in which the sensor is inscribed. This step change was not considered in electric strain gages due to the reasons: small Young modulus of the electric strain gages in comparison with the equivalent one of the structural surface and the measurements usually performed only after the bonding procedure.

In previous example one considered the influence of bonding technique for sensor attached to flat narrow surface (along the generatrix of the tube) on the measured strain. Now, the additional influence of the tube's curvature on strain change in rosettes is investigated. The procedure for calculating principal directions and values from strain rosette is based on matrix theory of symmetrical tensors of second rank [13]. The time traces for two optical rosettes are shown in Figures 4 and 5, where the

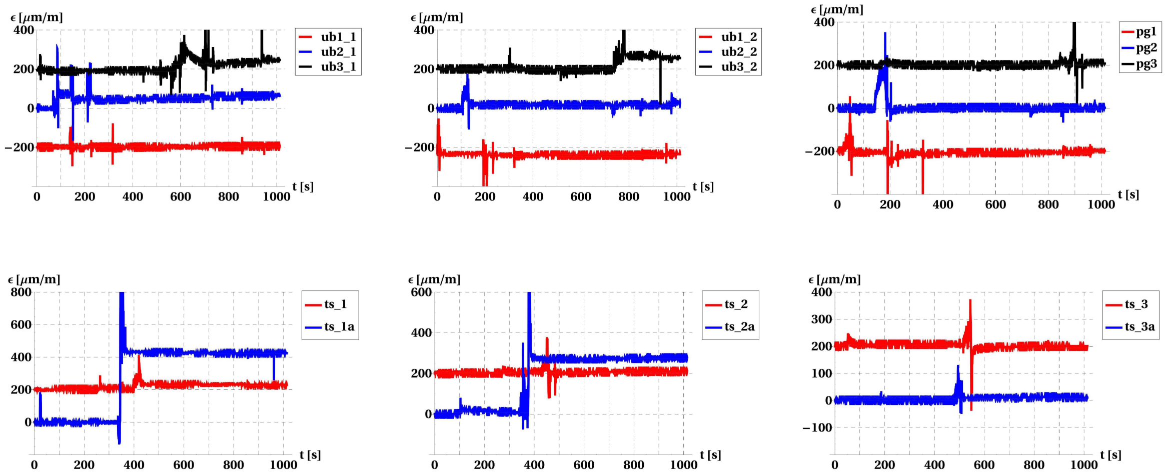

Figure 3 : Analysis of initial strain state of the single sensors before, during and after bonding. All time traces start from zero but additional constant strain ± 200 $\mu m/m$ was added to some curves for clearness purposes. Please note the strain step change for ts_1a and ts_2a sensors.

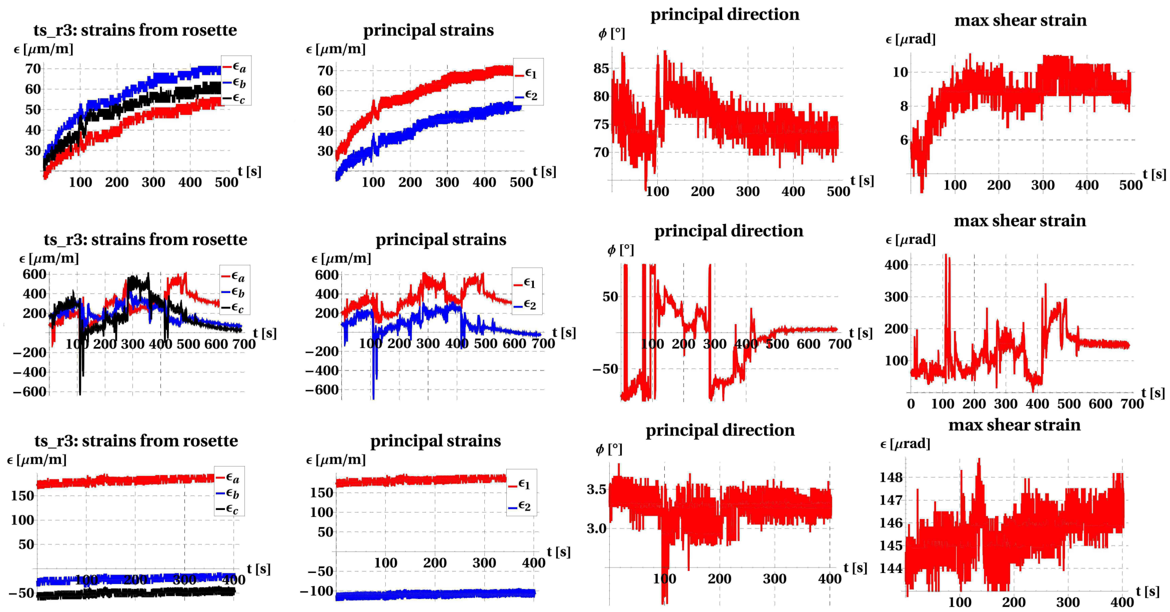

Figure 4 : Analysis of initial strain state of the rosette ts_r3, before (1st row), during (2nd row) and after (3rd row) bonding: measured and principal strains, directions, maximal shear strain.

strains before, during, and after bonding are represented by corresponding rows. The sensor "a" from the rosette should have been aligned along the generatrix of the tube. In practice, every rosette was slightly rotated around its center up to several degrees, see Figure 1.

Considering the first row in the Figures 4 and 5 which denote the strain state in the rosette before bonding, the increase in strain occurs which is probably caused by tension of optical fibres (the rosettes were hanging on the optical fibres and attached one by one). The second row represents bonding activity with lot of irregularities in traces. The irregularities were probably the result of changing transverse force applied to the rosette during bonding. The irregularities seem to be imposed on global

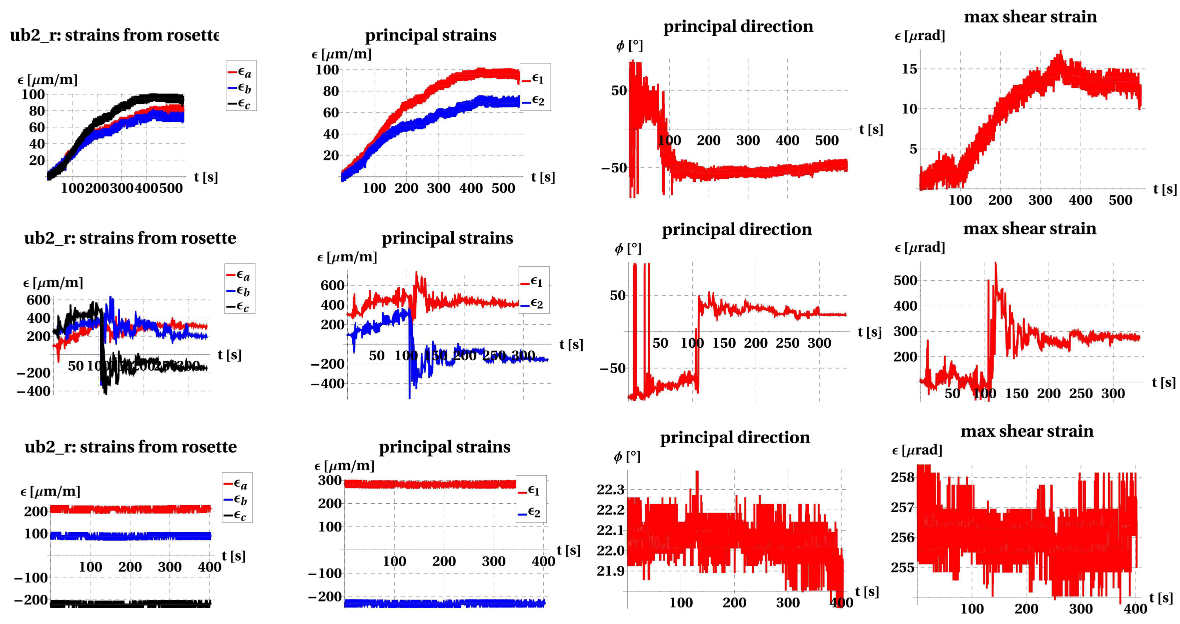

Figure 5 : Analysis of initial strain state of the rosette ub2_r, before (1st row), during (2nd row) and after (3rd row) bonding: measured and principal strains, directions, maximal shear strain.

changes resulted from plane strains induced in sensors. The third row in Figures 4 and 5 represents stable behavior achieved after some time. The initial bending and rotation of the optical rosettes causes significant changes with respect to expected state when rosette readings should not change in case of inextensional bending (for thin optical fibre bonded directly to the surface) or should change a little for optical fibre embedded in plastic cover at some distance from the surface ($\varepsilon_a = 0$, $\varepsilon_b = \varepsilon_c = const$, where *const* is dependent on the curvature of the tube and the distance between sensor and rosette's face).

Comparing the results for ts_r3 and ub2_r (bonded on smaller diameter tube) it seems that bigger strain changes are generated in rosettes attached to more curved surfaces. It should be noted that in both examples (single sensor and rosette) the strain change was connected with change of the sensor state not with strain changes in the structure. Analyzing the remaining rosettes, the principal values and directions were different for every rosette indicating that the bonding technique were not repeatable one.

The strained fiber behaves like guitar string and influences the sensor frequency response function. The initial step change due to bonding is important for experiment on model as well as on large structure. Influence of curvature is diminishing for large structures because the size dimensions of the sensors are significantly smaller than the radius of the structural tubes in offshore structures reducing the problem to bonding the rosette on locally flat surface.

2.2 Strains imposed by the change in boundary conditions

During installation of the tripod structure on the seabed, the foundation piles are driven through tripod PGs into the soil in order to provide sufficient force and moment reactions. These reactions assure that the structure is in dynamic equilibrium state under self-weight and operational loads. Introduced different stresses in PGs influence the state of stress in upper parts of the tripod. The knowledge of the measured, real stress levels in several locations is important in the determination of fatigue life for different parts of the structure.

The results for undamaged tripod shown in Figures 6 and 7 prove that the network of strain

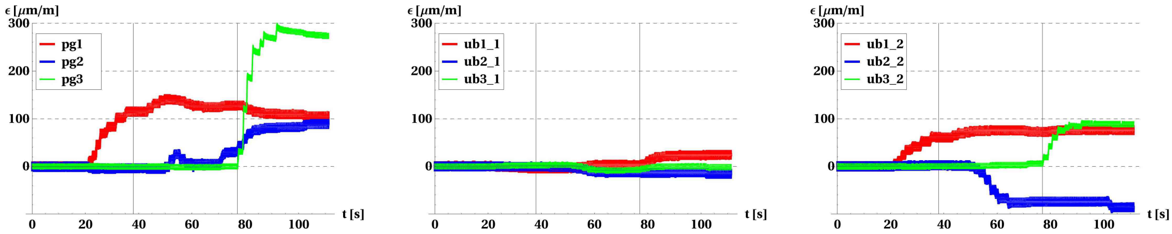

Figure 6 : The influence of change in the support conditions on strain readings of selected single sensors.

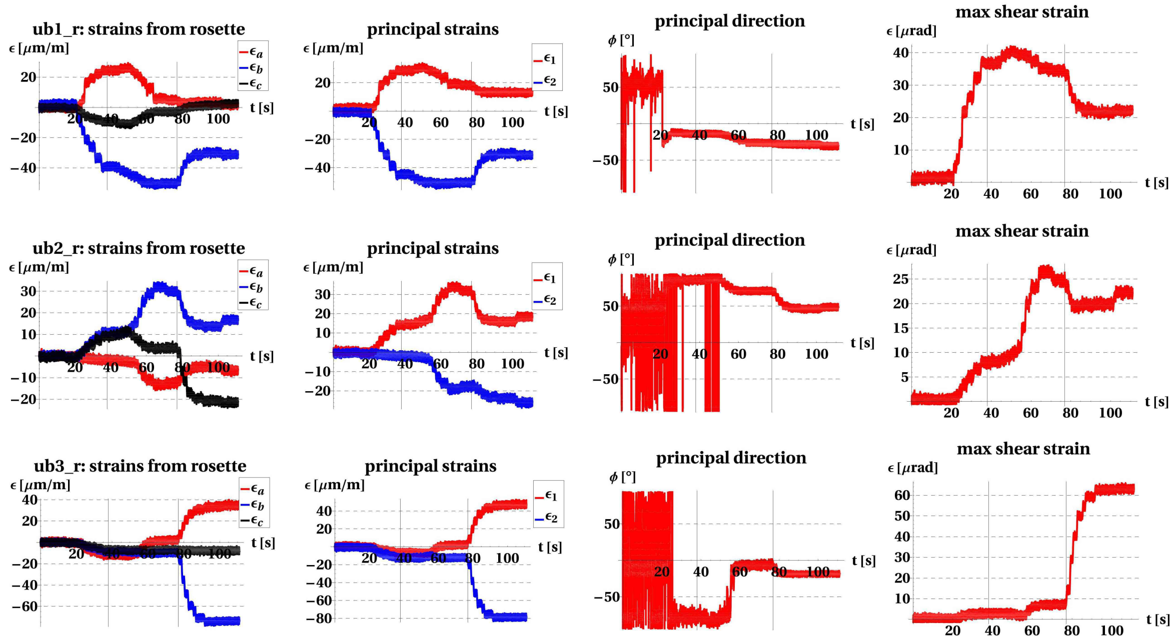

Figure 7 : The influence of change in the support conditions on strain readings of selected rosettes: ub1_r, ub2_r, ub3_r.

sensors is capable to discriminate emerging changes in different parts of the structure. The bolts have been tightened to the rings of PGs in the following order: PG1 (up to 37 s in time traces), PG2 (time between 37 and 78 s) and PG3 (from 78 s up to the end of the graphs) and these disjoint intervals are indicated by vertical lines in the figures. During the first 20 s of tightening the bolt in the ring of PG1 the strains are nearly zero because of clearance between bolt's head and the ring and the calculation of principal strain direction defined in the range $(-\pi/2, \pi/2)$ is unstable for this situation, see Figure 7.

Analyzing Figure 6, the higher strain responses are localized at the bottom part of the structure (graph 1 and 3) than in the middle part (graph 2). The responses can be easily linked with the order of tightening activities. Analyzing the output from rosettes in Figure 7, different tightening stages are recognized but the best results are obtained from maximal shear strain curves. In these curves the highest slopes are easily linked with the tightening activities in the corresponding PGs.

3. Conclusions

The influence of bonding procedures and the curvature of the surface on the initial strain generated in optical sensor may be concluded as follows: a) during the attachment of the sensor transient peak strain is generated in the optical fibre due to forces imposed on steel carrier; b) in rosettes bonded to curved surface additional strain is generated due to distance between surface and optical fibre embedded in plastic cover (extensional bending), and the irregularities in time traces are probably attributed to transverse forces applied on optical sensors; c) the state of initial strain in every rosette after bonding is different indicating the low repeatability of the bonding technique.

Somehow or other the geometrical symmetry of the tripod structure should manifest in strain response for sensors bonded in similar locations. The final state of strain after tightening all PGs show that the symmetry of the geometrical model is imitated only to some extent in real, intact structural model. Nonetheless, correctly located strain sensors are capable to indicate changes at the boundary between bottom part of the tripod model and the base. Moreover the location of sensors for such task need not to be bounded to regions close to that boundary. Sensors close to main node of the model and located on braces are also sensitive to these changes especially when the slope of shear strain is analyzed.

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