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A.Buranbayeva[1], **A.Zhussupbekov**[2]

[1] L.N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan
[2]Moscow State University of Civil Engineering, Moscow, Russian Federation
E-mail: 7011773434g@gmail.com, astana-geostroi@mail.ru

Commissioning Test of Distributed fiber-optics sensors during foundation monitoring of the Abu Dhabi Plaza construction project in Nur-Sultan City

Abstract. Distributed fiber optic cable is in increasing demand in civil engineering, especially in the field of structural condition monitoring. The characteristics of fiber optic cable have attracted the interest of engineers and researchers in recent years. This paper describes an operational test of a distributed fiber optic cable to determine its effectiveness in detecting cracks in concrete. A distributed fiber optic cable with internal fixed points was installed in the foundation slab of a high-rise building parking lot. Strain measurements from the fiber optic sensing cable were acquired and recorded using a Brillouin time domain optical analyzer throughout the test. The main purpose of the pre-commissioning tests is to check the accuracy error of the measurements. The accuracy error at any point on the cable is defined as the standard deviation of the repeated measurement values. This will show the reliability of the measured strain when interpreting the results.

Keywords: fiber optic cable, basement slab, high-rise buildings, fiber-optic sensors, civil engineering.

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Introduction

Structural condition monitoring is increasingly being used in civil engineering as an effective means to improve facility safety and optimize the cost of operating and maintaining structures. The data obtained from monitoring is used to optimize the operation, maintenance, repair and replacement of the structure based on reliable and objective data. Detection of current damage can be used to detect deviations from design performance. Monitoring data can be integrated into structural management systems and improve decision quality by providing reliable and objective information. A distributed fiber optic sensor (DFOS) based on Brillouin backscattering technology has many attractive features such as small size, good structural compatibility, light weight, immunity to electromagnetic interference, etc. Traditional control sensors, such as load cells, often require a large amount of cabling to support them. The cost of cabling limits the suitability of traditional sensors for monitoring. However, a distributed fiber sensor is capable of measuring strain at every point along a standard optical cable, which means that an appropriately installed fiber can potentially replace many traditional point sensors. It is therefore widely accepted as a cost-effective structural monitoring tool.

Literature Review

SHM systems have been used in civil engineering since the early 1980s [1]. A literature review of SHM systems was first presented by Doebling et al. in 1996, summarizing hundreds of publications through 1995. The interest in the ability to monitor a structure and detect damage at the earliest possible stage is pervasive throughout the civil engineering communities. Current damage-detection methods are either visual or localized experimental methods such as acoustic or ultrasonic methods, magnet field methods, radiographs, eddy-current methods and thermal field methods. All of these experimental techniques require that the vicinity of the damage is known a priori and that the portion of the structure being inspected is readily accessible. Subjected to these limitations, 2 of these experimental methods can detect damage on or near the surface of the structure. The need for additional global damage detection methods that can be applied to complex structures has led to the development of methods that examine changes in the vibration characteristics of the structure [2]. Damage or fault detection, as determined by changes in the dynamic properties or response of structures, is a subject that has received considerable attention in the literature. The basic idea is that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties will cause changes in the modal properties. Ideally, a robust damage detection scheme will be able to identify that damage has occurred at a very early stage, locate the damage within the sensor resolution being used, provide some estimate of the severity of the damage, and predict the remaining useful life of the structure.

The effects of damage on a structure can be classified as linear or nonlinear. A linear damage situation is defined as the case when the initially linear-elastic structure remains linear-elastic after damage. The changes in modal properties are a result of changes in the geometry and/or the material properties of the structure, but the structural response can still be modeled using a linear equation of motion. Nonlinear damage is defined as the case when the initially linear-elastic structure behaves in a nonlinear manner after the damage has been introduced. One example of nonlinear damage is the formation of a fatigue crack that subsequently opens and closes under the normal operating vibration environment. Other examples include loose connections that rattle and nonlinear material behavior. A robust damage-detection method will be applicable to both of these general types of damage. The majority of the papers summarized in this review address only the problem of linear damage detection. They proposed the Classification table for damage identification methods, which is a compendium that classifies various methods of damage identification and model updating in chronological order [2].

Sensors and equipment. Combined deformation and temperature sensors DiTeSt SMART profile are designed for distributed deformation (average deformation) and temperature monitoring over long distances using BOTDA (Brillouin scattering) technology.

The DiTeSt SMARTprofile sensor consists of two bonded and two free single-mode optical fibers embedded in a polyethylene thermoplastic profile. The stapled fibers are used for strain monitoring, while the free fibers are used for temperature measurement (quantitative measurement if the strain sensor is <0.2%, qualitative if the strain is >0.2%) and to compensate for temperature effects on the stapled fibers. For redundancy, two fibers are included for strain and temperature monitoring. The profile itself provides good mechanical, chemical and temperature resistance.

The small profile size makes the sensor easy to transport and install by embedding in concrete or mortar, bonding or clamping.

The SMARTProfile sensor is designed for use in environmental conditions commonly found in civil, geotechnical and oil and gas applications. However, this sensor should not be used in extreme temperature environments or environments with corrosive chemicals. It is not recommended for installation under constant ultraviolet radiation (e.g. sunlight) without an additional cover or protection with aluminum tape.

The SMARTprofile sensing cable is supplied on reels with all necessary accessories such as terminations and connectors.

Optical Time Domain Analysis (BOTDA). The principle of the BOTDA sensor system is shown in Figure 1 and a typical BOTDA analyzer is shown in Figure 2. BODTA technology is a proven, reliable system for determining load distribution along the pile shaft and pile toe. Light waves traveling through the fiber optic cable react with the glass material in the fiber. The reaction causes a change in density as well as a change in frequency, i.e., a Brillouin frequency shift. By resolving the frequency shift and time propagation, a continuous total strain profile can be determined [3].

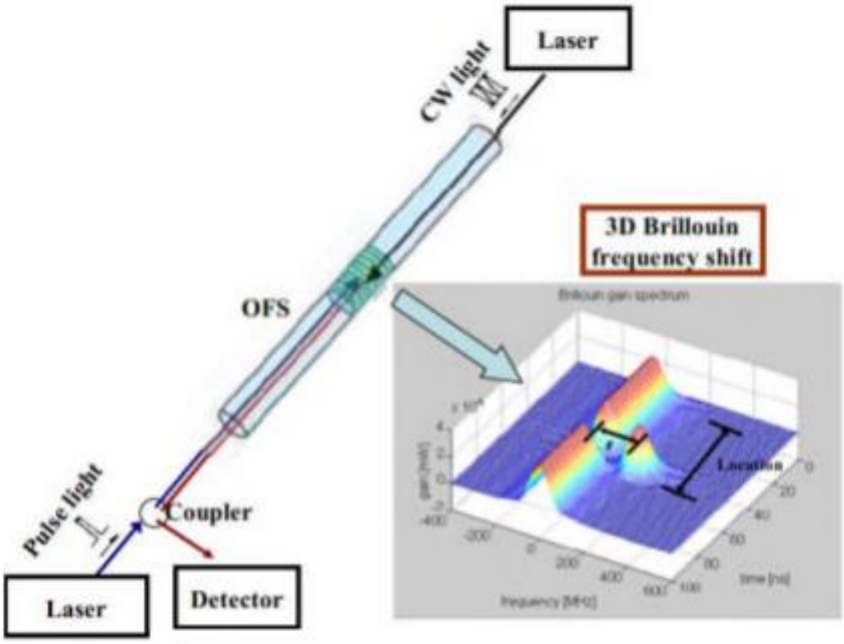

Figure 1 - Principle of BOTDA sensor system [4]

The main advantages of fiber optic sensors are the use of natural glass, which is immune to electromagnetic interference, resistant to corrosion and inert to chemical reactions. Fiber optic sensors are very versatile and can be used safely in many harsh environments such as high voltage, marine or explosive environments. In addition, DFOS cables are thin and therefore make it easy to install on the reinforcement cage without disturbing the concreting process. DFOS cables embedded in concrete piles are durable and can be measured for many years. Consequently, DFOS is also very suitable for long-term monitoring. Finally, compared to conventional sensors, DFOS provides a continuous measurement of deformation along the pile rather than discrete measurements at a few specific points.

The analyzer measures strain by transmitting pulses of light along the fiber and analyzing the frequency spectrum of the backscattered light. The optical budget of the analyzer can be increased by increasing the pulse duration, measured in nanoseconds, which reduces its attenuation. However, if the pulse duration is too long, the scattered light from the leading edge of the pulse begins to interfere with the scattered light from the trailing edge of the pulse, and the analyzer cannot distinguish one from the other. This imposes a limit on the minimum distance at which the strain value can be interpreted by the analyzer. This distance is called the spatial resolution and can be likened to the width of the averaging window for the sample point [2-3].

Spatial resolution up to 2 cm is achievable by some analyzers on the market, but because of the trade-off between optical budget and spatial resolution, this comes at the expense of the optical budget, which is only about 2 dB at this low spatial resolution. To achieve the required optical budget of 11 dB the spatial resolution is typically at least 0.5 m.

Although the spatial resolution limits the minimum distance at which the strain value can be interpreted, the analyzer is still capable of taking multiple measurements at small intervals along with the fiber.

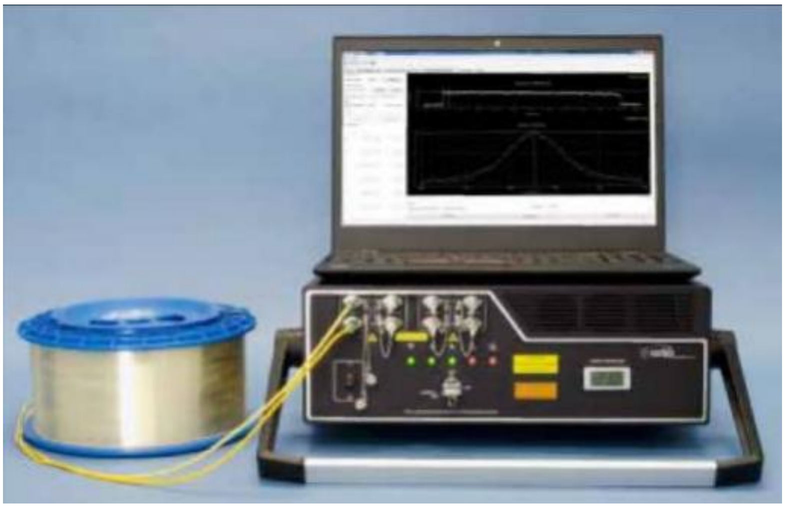

Figure 2 - A typical BOTDA analyzer

Installation Procedures. The fiber optic cable used for the bored pile is shown in Figure 3. The single strand single-model optical fiber is reinforced with multiple strands of steel wire and a polyethylene jacket.The fiber optic sensor is 0.125 mm in diameter with a 0.25 mm cable coating, and the total cable diameter is 5 mm. The glass core is firmly fastened together with the coating to allow full strain transfer from the coating to the inner glass strand.

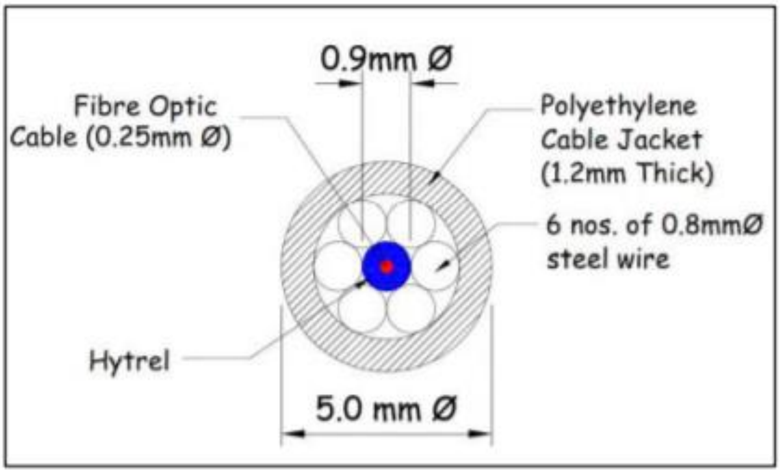

Figure 3 - Configuration of a strain-sensitive optical cable

It is necessary to prevent fiber fracture, since mounting the fiber under a hollow slab makes any fracture repair virtually uncorrectable. Fracture along a localized crack in the slab is prevented by fixing the fiber only at individual points, rather than attaching the fiber to the slab continuously along its entire path. The length of the unbound section between two adjacent attachment points is called the gauge length. Preventing overstretching depends on the fiber undergoing average surface deformation of the slab along the gauge length instead of experiencing maximum instead of maximum localized deformation near the crack [4].

A gauge length of two meters was considered sufficient to limit the average expansion-induced strain below the allowable strain limit.

An alternative to discrete fixation is continuous bonding of the fiber along its entire length, but it is necessary to allow adhesive bonding when the specified shear stress is exceeded. In practice, it is difficult to achieve consistent adhesive flow under site conditions and there is a risk of either inaccurate deformation display if premature or fiber failure if output is delayed [5].

Test results. The main purpose of commissioning tests is to check the accuracy error of measurements at the construction site. Accuracy error at any point of the cable is defined as the standard deviation of repeated measurement values. This will show the reliability of the measured strain when interpreting the results.

Two tests were performed in which readings were recorded once at 15-minute intervals over three days for each test. At each measurement point, the standard deviation of the readings was determined and a graph was plotted as a function of the distance along the cable.

In the first test, the analyzer is constantly on, while in the second test, the analyzer is turned off after each reading. is turned off after each reading. These two different tests are performed because one of the most important factors causing accuracy error is the thermal drift in the electronic components inside the analyzer.

Standard Deviation Graphs [6]
(A) Block R Vertical

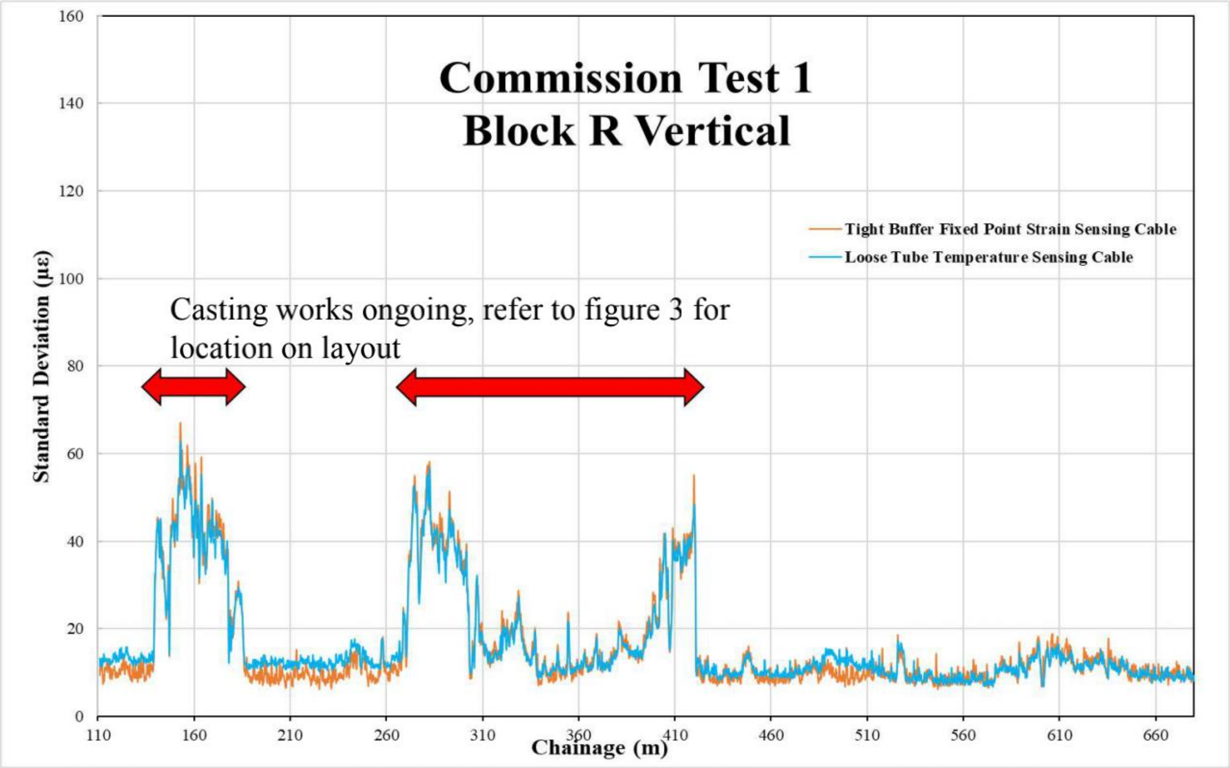

Figure 4: Commission test 1 standard deviation block R vertical

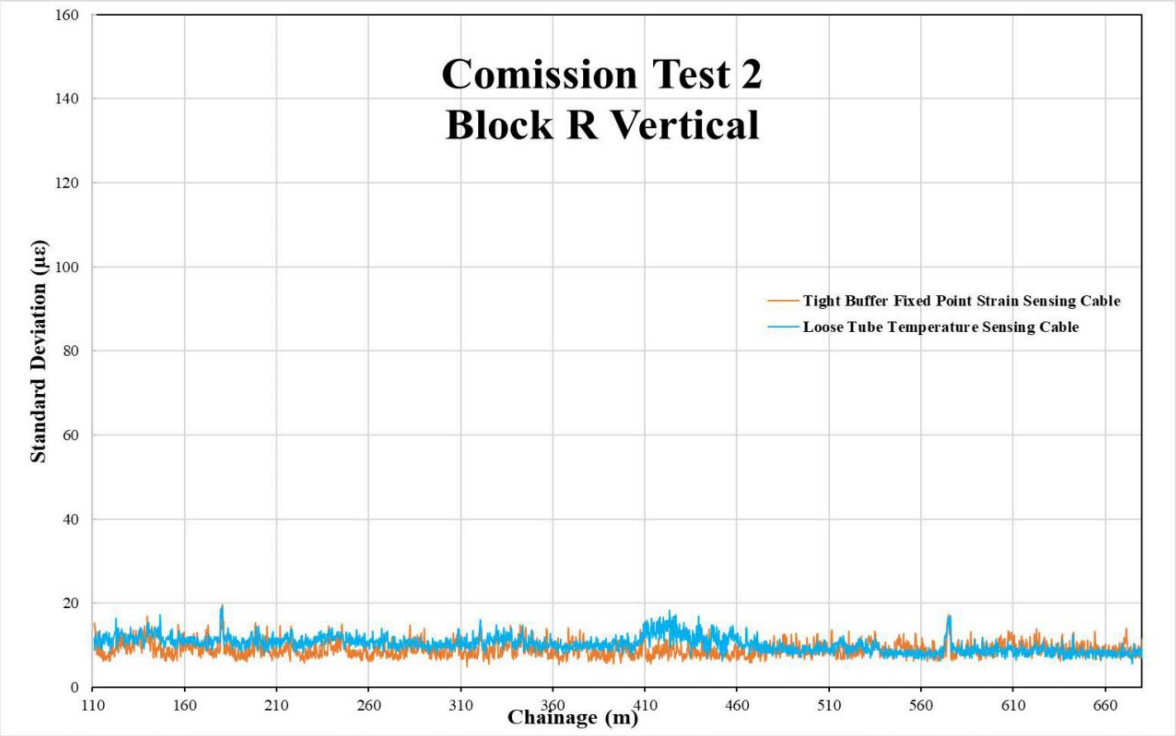

Figure 5: Commission test 2 standard deviation block R vertical

Figure 6: Slab casting works were ongoing at the above location in Block R during

commission test

(B) Block R Horizontal

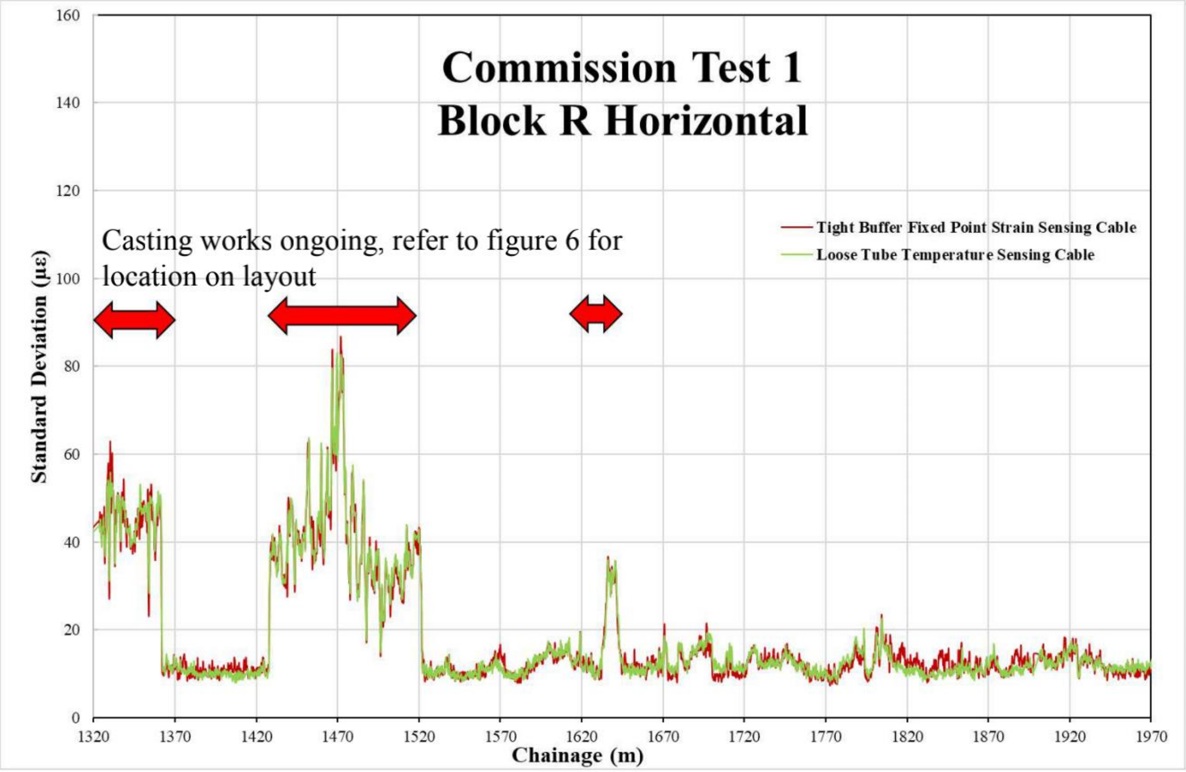

Figure 7: Commission test 1 standard deviation block R horizontal

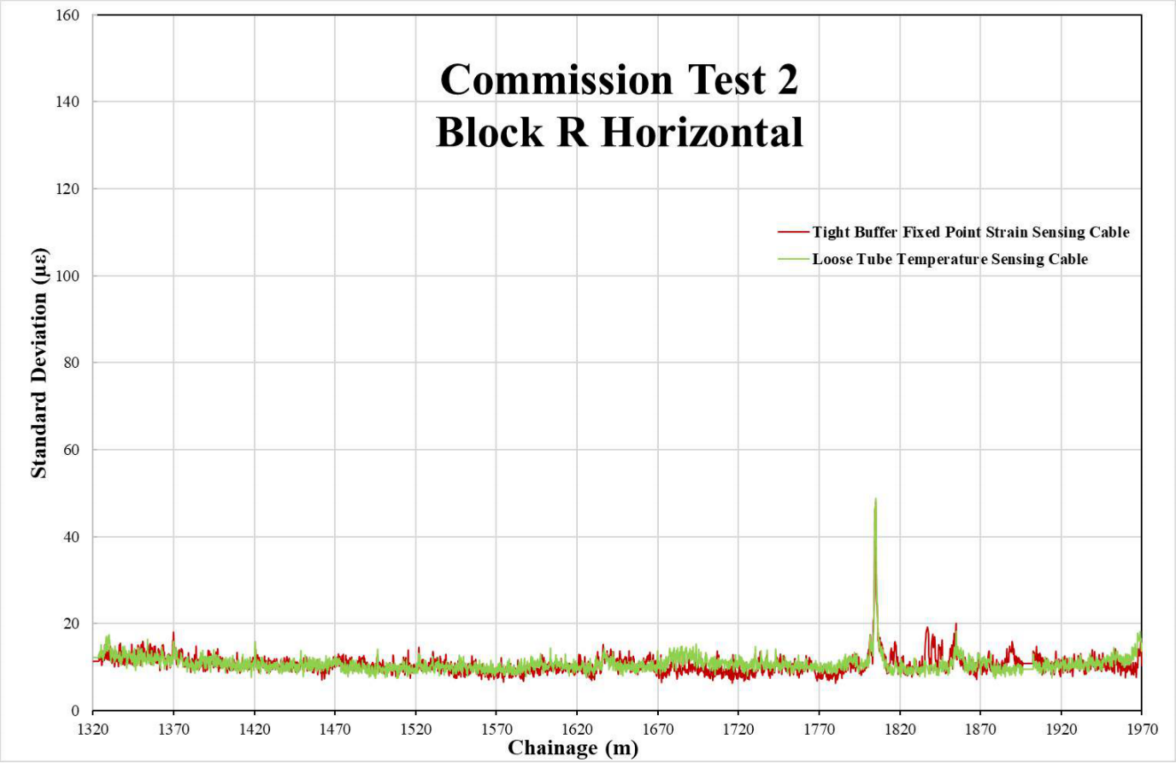

Figure 8: Commission test 2 standard deviation block R horizontal

Figure 9: Slab casting works were ongoing at the above location in Block R during commission test

Conclusion

The main objective of the commissioning test is to check the measurement precision error. The precision error at any point along the cable is defined as the standard deviation of repeated measurement values. This will indicate the reliability of the measured strain during interpretation of results. The primary objectives of the test are stated below:

No.	Descriptions	Remarks
1	Commissioning Test 1: - To take measurement at every 15 minutes for 3 days. - To keep analyzer continuously on. - To plot standard deviation with distance along the fibre optic cable.	**Complied.**
2	Commissioning Test 2: - To take measurement at every 15 minutes for 3 days. - To power off analyzer after each measurement. - To plot standard deviation with distance along the fibre optic cable.	**Complied.**

The commissioning test was successfully implemented and achieved all the primary objectives.

The commission test results were able to capture temperature changes caused by the curing of concrete during the testing as shown in Figures 4 to Figure 9. The temperature changes were significant at certain locations at Block R where the slab casting process was ongoing during the measurement time. Similar measurement trends between both temperature and strain sensing cables indicate that the strain changes were caused by a change in temperature rather than structural movement.

By comparing the standard deviation of the first and second test, the results have shown that both tests have a very similar magnitude of standard deviation except for those areas where there were significant temperature changes. Therefore, for the current analyzer used, the thermal shift in electronic components does not affect the precision error when the analyzer is powered off.

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6. Report of the Commissioning Test to fulfil the requirements as stated in Golder's report (ADP-135100-001), Section 3.12.2 - Item 4.

А.Буранбаева[1], А.Жүсүпбеков[2]
[1]Л.Н. Гумилев атындағы Еуразия ұлттық университеті, Нұр-Сұлтан, Қазақстан
[2]Мәскеу мемлекеттік құрылыс университеті, Мәскеу, Ресей

Нұр-Сұлтан қаласындағы Абу-Даби Плаза құрылысы жобасының іргетасын бақылау кезінде таратылған талшықты-оптикалық сенсорлардың өнімділігін сынау

Аңдатпа. Таратылған талшықты-оптикалық кабель азаматтық құрылыста, әсіресе құрылымдық денсаулық мониторингі саласында сұраныс артып келеді. Талшықты-оптикалық кабельдің сипаттамалары соңғы жылдары инженерлер мен зерттеушілердің қызығушылығын тудырды. Мақалада бетондағы жарықтарды анықтаудағы тиімділігін анықтау үшін бөлінген талшықты-оптикалық кабельдің өнімділік сынағы сипатталады. Көпқабатты автотұрақтың іргетас тақтасына ішкі бекітілген нүктелері бар бөлінген талшықты-оптикалық кабель орнатылды. Талшықты-оптикалық датчик кабелінен кернеу өлшемдері сынақ барысында оптикалық Brillouin уақыт доменінің анализаторы арқылы алынды және жазылды. Іске қосу сынақтарының негізгі мақсаты өлшеу дәлдігінің қателігін тексеру болып табылады. Кабельдің кез келген нүктесіндегі дәлдік қателігі қайталанатын өлшемдердің стандартты ауытқуы ретінде анықталады. Нәтижелерді интерпретациялау кезінде өлшенген деформацияның сенімділігін көрсетеді.

Кілт сөздер: талшықты-оптикалық кабель, жертөле тақтасы, көпқабатты үйлер, талшықты-оптикалық сенсорлар, құрылыс инженериясы.

А.Буранбаева[1], А.Жусупбеков[2]
[1]Евразийский национальный университет им.Л.Н. Гумилева,Нур-Султан, Казахстан
[2]Московский государственный строительный университет, Москва, Россия

Эксплуатационные испытания распределенных волоконно-оптических датчиков при мониторинге фундамента строительного проекта Abu Dhabi Plaza в городе Нур-Султан

Аннотация. Распределенный волоконно-оптический кабель пользуется все большим спросом в гражданском строительстве, особенно в области мониторинга состояния конструкций. Характеристики волоконно-оптического кабеля в последние годы привлекают интерес инженеров и исследователей. В данной статье описывается эксплуатационное испытание распределенного волоконно-оптического кабеля для определения его эффективности в обнаружении трещин в бетоне. Распределенный волоконно-оптический кабель с внутренними фиксированными точками был установлен в фундаментной плите парковки высотного здания. Измерения деформации от оптоволоконного чувствительного кабеля были получены и записаны с помощью оптического анализатора временной области Бриллюэна на протяжении всего испытания. Основной целью пуско-наладочных испытаний является проверка погрешности точности измерений. Погрешность точности в любой точке кабеля определяется как стандартное отклонение значений повторных измерений. Это покажет надежность измеренной деформации при интерпретации результатов.

Ключевые слова: волоконно-оптический кабель, подвальное перекрытие, высотные здания, волоконно-оптические датчики, гражданское строительство.

Information about authors:

Zhussupbekov A. – Doctor of Technical Sciences, Professor, Consultant of Department of Soil Mechanics and Geotechnics of Moscow State University of Civil Engineering, Moscow, Russia.

Buranbayeva A. – PhD student of «Civil Engineering» department of Faculty of architecture and construction of L.N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan.

Жүсүпбеков А.Ж. - профессор, техника ғылымдарының докторы, Мәскеу мемлекеттік құрылыс университетінің Топырақ механикасы және геотехника кафедрасының консультанты, Мәскеу, Ресей.

Буранбаева А.М. - Л.Н. Гумилев атындағы Еуразия ұлттық университеті Сәулет және құрылыс факультетінің «Құрылыс» кафедрасының PhD докторанты, Нұр-Сұлтан, Қазақстан.