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Fibre Optic Embedded Sensors for the Health Monitoring of Offshore Structures

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ABSTRACT: The safest and most durable structures are those that are well managed. Measurement and monitoring often have essential roles in management activities. Structural Health Monitoring (SHM) is a process aimed at providing accurate and in-time information concerning structural condition and performance. The data resulting from a monitoring programme are used to optimize the operation, maintenance, repair and replacing of the structure based on reliable and objective data. The main target of the structural health monitoring system is to extract maximum data about the representative parameters (such as average strains and curvatures, average shear strain, deformed shape and displacement, crack occurrence and quantification). Thus, it is necessary to place the sensors in representative positions on the structure. Also, Successful monitoring strategy must grantee a continuous record for the sensor readings in comparison with predefined warning values. If predefined warning threshold was reached, then the alert status was automatically activated.

In order to achieve the aims of monitoring it is necessary to employ a good monitoring strategy. Finite element Method (FEM) is utilized to predict the structural response of the structure and to specify the locations of stresses hot spots. Based on which, all regions of the structure will be equipped by sensor combination which is the best manner corresponds to the expected strain field of the structure. The combination of FEM and SHM offers a good basis for making decisions concerning the monitoring strategy. A good monitoring strategy can provide excellent results with relatively limited budget.

Case study of the most frequent types of structure in offshore platforms is presented schematically in the current study. Detailed Numerical modeling for the structure is presented based on which the sensors topologies are decided in attempts to achieve successful heath monitoring strategy for such structure.

1 STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) is defined as the process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure. It consists of permanent continuous, periodic or periodically continuous recording of representative parameters, over short or long terms. Although sometimes SHM refers to damage detection, it could be used to refer to the process of quality assurance of the properties of new structures, long-term monitoring of an existing structure, structural control and many others. In the most general terms, damage can be defined as changes introduced into a system that adversely affects its current or future performance.

Structural Health Monitoring (SHM) provides a vital link between monitored structures and a central monitoring site. This allows many structures to be monitored at a central site and many activates could be decided such as modifications to an existing structure; monitoring of structures affected by external works; monitoring during demolition; structures subject to long-term movement or degradation of materials; feedback loop to improve future design based on experience; fatigue assessment; novel systems of construction; assessment of post-earthquake structural integrity; decline in construction and growth in maintenance needs; and the move towards performance-based design philosophy.

The current research is focused on the development and optimization of a Structural Health Monitoring (SHM) technique to detect damage initiation for offshore structures. In the first part of the current study, Finite Element Analysis was conducted to determine the hot spot stresses for a case study (Hibernia offshore platform). That enables continuous health monitoring of the structure as well as the capability to detect and monitor locally damaged and overstressed spots. This numerical modeling will help the design engineers to choose the suitable locations for SHM sensors to optimize the distribution of the FBG sensors in such thick structures. The proposed methods will be used for early detection of structural damage of offshore structures. Through the use of these methods operators of such structures will be able to maintain safe and economic operation of their facilities. Maintenance costs as well as shutdown cost will be reduced. In addition danger to human life and the environment will be reduced. Meanwhile, the ideal locations for using FBG sensors will be identified.

2 OPTICAL FIBRE BRAGG GRATING SENSORS AND OPERATING PRINCIPLE

Fibre Bragg grating (FBG) sensors are one of many fibre optic sensor technologies that are currently being used in SHM systems. The sensors operate by detecting a shift in the wavelength of the reflected maximum due to applied strain. The main advantage of FBGs for mechanical sensing is that these devices perform a direct transformation of the sensed parameter to optical wavelength, independent of light levels, connector or fibre losses, or other FBGs at different wavelengths. A fibre Bragg grating is wavelength-dependent filter/reflector formed by introducing a periodic refractive index structure, with spacing on the order of a wavelength of light, within the core of an optical fibre. Whenever a broad-spectrum light beam impinges on the grating, it will have a portion of its energy transmitted through, and another reflected off as depicted in Fig. 1. The reflected light signal will be very narrow (few nm) and will be centered at the Bragg wavelength that corresponds to twice the periodic unit spacing (**Λ**). Any change in the modal index or grating pitch of the fibre caused by strain, temperature, displacement, or cracks in buildings will result in a Bragg wavelength shift. An FBG is a region of germanium-doped glass fibre core that has been exposed to UV radiation using a ‘phase mask’ to fabricate a periodic ‘grating’ of material with a modulated index of refraction. This precise spacing, called the ‘pitch’, reflects incident light in a narrow band centered about the ‘Bragg’ wavelength, defined by:

$$\lambda_o = 2\,n\,\Lambda \tag{1}$$

where λ_o is the Bragg wavelength, n is the average effective index of refraction of the grating and Λ is the pitch spacing, as shown in Fig. 1. The FBG also provides a linear response based on the measurement of wavelength shift ($\Delta\lambda$) due to straining of the gage. Measuring $\Delta\lambda$ provides a means of determining the strain according to the equation:

$$\varepsilon = \frac{1}{G_f}\left(\frac{\Delta\lambda}{\lambda_o} - \beta\Delta T\right) \tag{2}$$

where $\Delta\lambda = \lambda - \lambda_o$, G_f is the FBG gauge factor and is a function of the Poisson's ratio, strain-optic constants of the fibre, and refractive index, typical values for G_f ranges from 0.75-0.82, ε is the strain, β is the thermal coefficient and ΔT is the temperature change relative to the temperature at installation. Typical wavelength shifts are 1.2 pm/(με) for strain and 10 pm/ ($1/G_f$) for the temperature of Bragg gratings around 1530 nm.

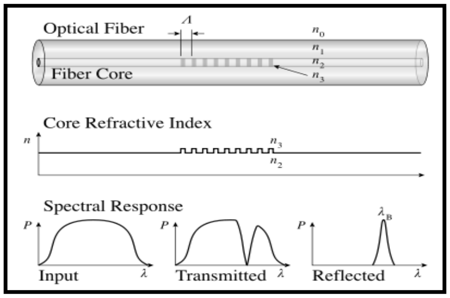


Figure 1. Transmission and reflection spectra of a fibre bragg grating

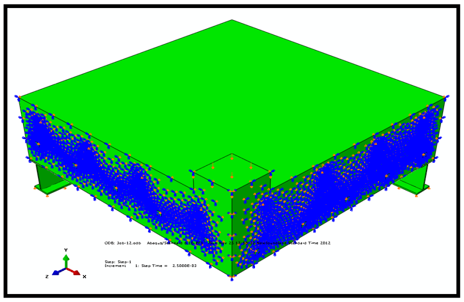


Figure 2. Loading and boundary conditions

3 HEALTH MONITORING OF SLAB-COLUMN CONNECTION

A two-way slab is a structural element subject to biaxial bending, torsional moment, as well as membrane and shear forces. Structural monitoring of two-way slab element poses some challenges that require careful selection of effective sensors locations or a large number of sensors will be required for slab monitoring, which can be very costly. In order to reduce the monitoring costs, it is recommended to monitor only the critical damage zones in the slab. In order to optimize the number of sensors used, a numerical Finite Element Model FEM was conducted to obtain the hot spots of the stresses, and as a result, specify accurate sensors locations.

3.1 FEM of slab-column connection

A non-linear finite element analysis (FEA) was carried out to predict the structural response of the tested full-scale slab-column connection. The computer code ABAQUS version 6.7-1 was used to perform the numerical analysis for the tested reinforced concrete panels. The model takes into consideration the degradation of the elastic stiffness induced by plastic straining both in tension and compression. Also, this model assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material.

In this study, one quarter of the panel was modeled, as two symmetry plans in the test set-up was utilized when building the FE models. The concrete and the steel rebars in the reinforced concrete panels were adapted by eight-node linear brick elements C3D8 with full Gaussian integration rule over the element face. The contact between the reinforcement and concrete was considered. The boundary conditions for the model were set along the middle of the panel in X- and Z- plans of symmetry, and at the four corner points of the bottom surface in Y- directions. Fig. 2 shows loading and boundary conditions for a typical finite element model.

3.2 FEM results of slab-column connection

The FEA was performed to obtain the hot spot stress at each critical location on the structural slab-column connection. The finite element results in Figs. 3, 4 show the hot spots of stresses for flexure and shear. Based on the finite element results, the layout of FBG sensor was decided.

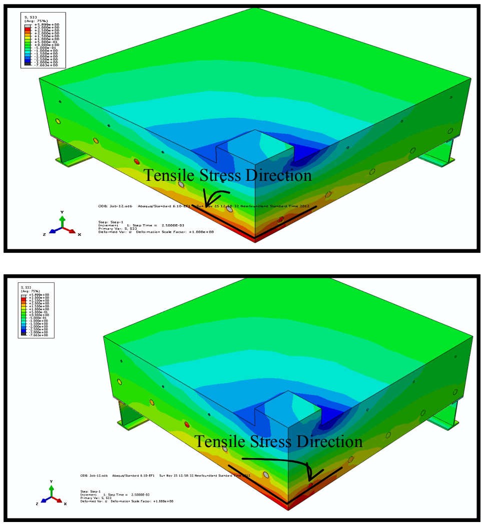


Figure 3. Flexure stress distribution in S_{11} and S_{33}

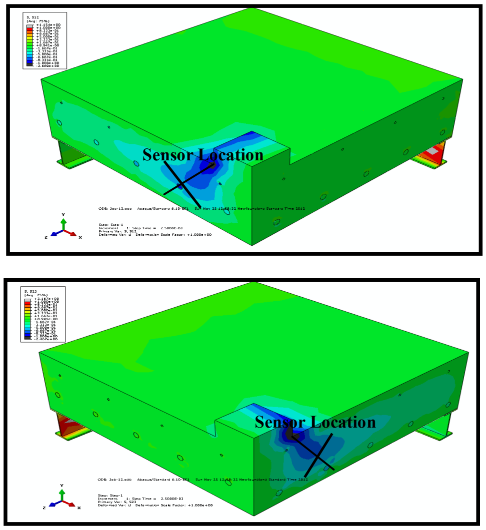


Figure 4. Shear stress distribution in S_{11} and S_{33}

3.3 Experimental program

3.3.1 Test slabs

One full-scale specimen was instrumented and tested in the described experimental program. Test was conducted on a model of a two-way slab part enclosed by contra-flexure lines on which bending moment values vanish. The reinforced concrete slab was square with 2600 mm side length and 400 mm thickness. Column stub was cast at the central of the reinforced concrete slab to apply a central load using a hydraulic jack, as presented in Fig. 5.

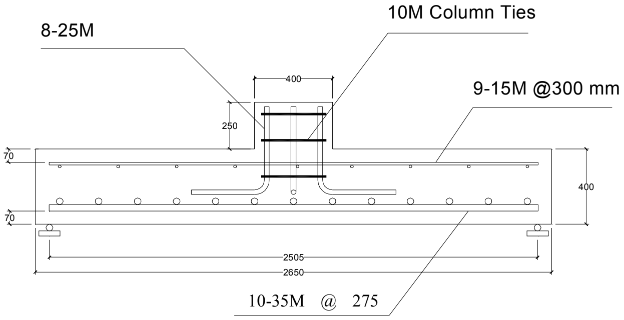


Figure 5. Slab reinforcement and dimensions

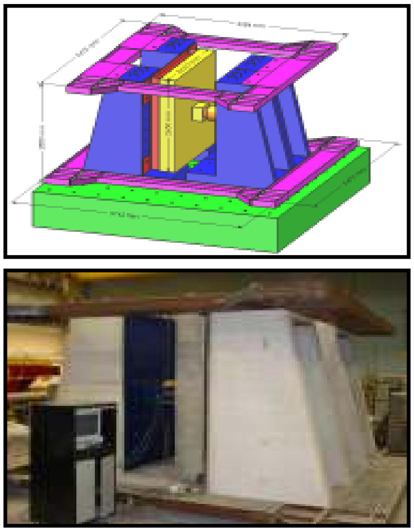


Figure 6. Test set-up and the specimen

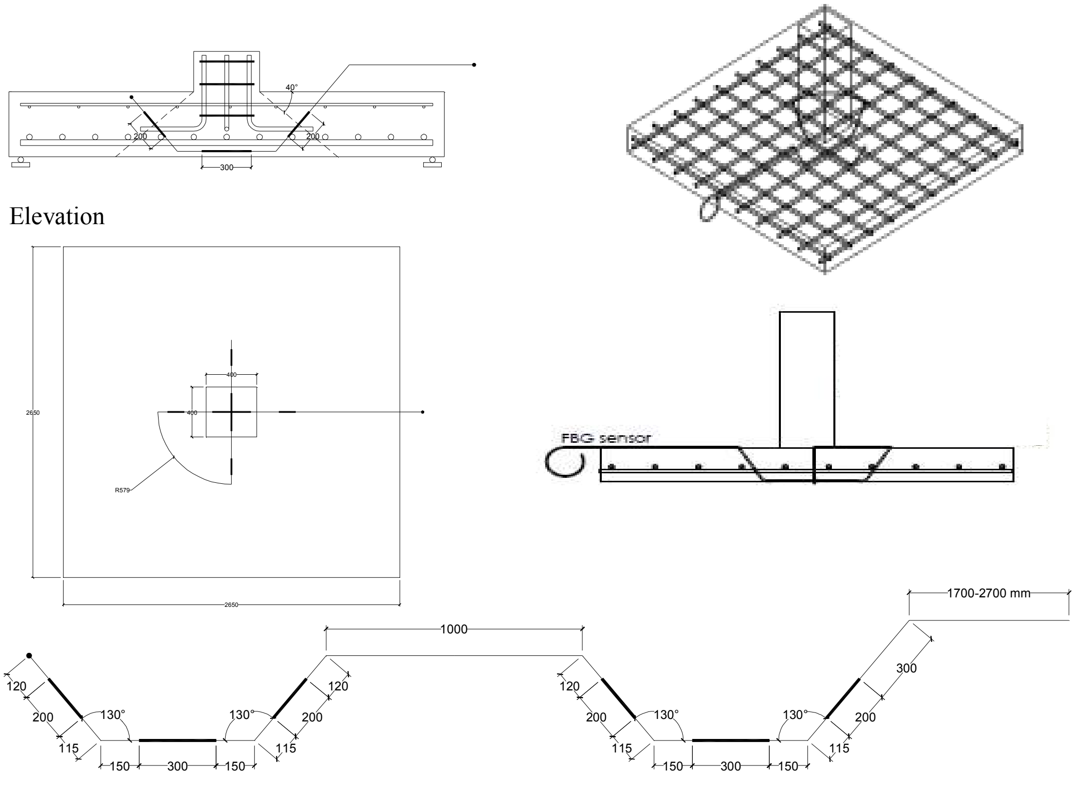
The object of this experimental investigation is to study the efficiency of SHM technique for detecting stresses/strains for an existed structure to assessing the ongoing, in-service performance of important infrastructures such as offshore platforms. The investigation includes using multiplexed long FBG sensors to a 400 mm thick concrete plate

3.3.2 Test set-up

A new test setup was designed and fabricated in the structural laboratory at MUN. The main function of this setup is to apply direct transverse load through hydraulic jack. A hydraulic jack was fixed to the frame and was used to apply a central load on the column stub in a horizontal position. The applied load and the displacement of the actuator were measured by its internal load cell and linear voltage displacement transducer (LVDT), respectively. The details of this test setup are shown in Fig. 6.

3.3.3 FBG sensors array layout

Fiber Bragg Grating (FBG) sensors are one of many fiber optic sensor technologies that are currently being used in structural health monitoring systems. The sensors operate by detecting a shift in the wavelength of the reflected maximum due to applied strain. Due to their multiplexing capability, fiber Bragg grating sensors show potentials for applications in the field of distributed sensing in "smart structures", into which fiber Bragg grating sensor arrays can be embedded to measure the parameters such as strain, stress, temperature, cracks, acceleration and vibration of the structure. Based on the FEM results for the slab-column connection tested in the current study and presented in Fig. 4, the lay out of the FBG is illustrated in Fig. 7 as the sensors are focused in the hot spots for flexural and shear stresses.



Plan

Figure 7. FBG sensor arrangement

3.3.4 Test procedure and results

The plate was tested in a vertical position in order to detect and mark the cracks as they developed. The load was applied to the plate concentrically through the stub column. The load was applied by means of a hydraulic actuator. During testing, the plate was carefully inspected and cracks were marked at each load increment. Each load increment was given enough time to allow for monitoring and marking flexural cracks as they developed.

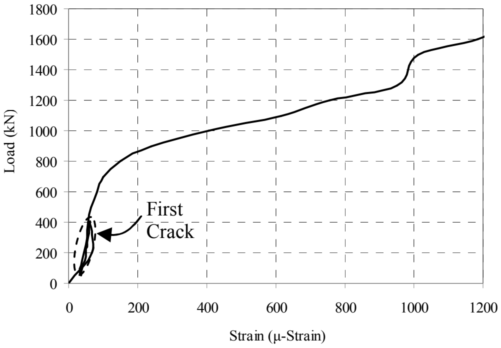


Figure 8. Concrete tensile strain versus the applied load

Concrete tensile strains were recorded using an embedded long FBG strain sensor with a gauge length equal to 300 mm. Figure 8 shows the concrete tensile strain versus the applied load curve. In general, the concrete strains indicated that as the load was increased, the concrete tensile strain increased gradually up to the initiation of first crack. The long FBG sensor was able to capture the initiation of the first and second transverse flexural cracks; this is indicated by a sudden increase (shift) in the concrete tensile strain value. The first crack occurred at a load approximately equal to 250 kN that represented 14.5% of the punching failure load. The first crack width could be calculated by multiplying the difference in the concrete tensile strain (110 με) by the gauge length value (300 mm), and it is equal to 0.04 mm. The same procedure could be used to calculate the width of the second crack as well.

4 CASE STUDY (HIBERNIA OFFSHORE PLATFORM)

In Atlantic Canada, the oil and gas industry operates offshore. These environments are substantially different than onshore operations, and can pose harsh and difficult operating conditions. Our responsibility is to safeguard marine life and ecosystems so that they are not harmed by oil and gas production. In this section in the current study, finite element modeling for Hibernia offshore platform was performed to locate the hot spot stresses for that GBS concrete structure. That enables continuous health monitoring of the structure as well as the capability to detect and monitor locally damaged and overstressed spots. These design guidelines will help design engineers to choose the suitable locations for SHM sensors to optimize the distribution of the FBG sensors in such thick structures.

4.1 Finite element analysis (FEA) to Hibernia platform

A non-linear finite element analysis (FEA) was carried out to predict the structural response of the platform. The computer code ABAQUS version 6.7-1 was used to perform the numerical analysis for the tested reinforced concrete panels. C3D8 is a general purpose linear brick element, with fully integration points, and with translations in the nodal x-, y-, and z-directions. The concrete were adapted by eight-node linear brick elements C3D8 with full Gaussian integration rule over the element face. Figure 9 shows the three-dimensional finite-element models for the gravity offshore platform that was simulated in the current study. Realization of the full potential of the finite element modeling to simulate the structural response is an important tool to predict the structural response of the various offshore platforms.

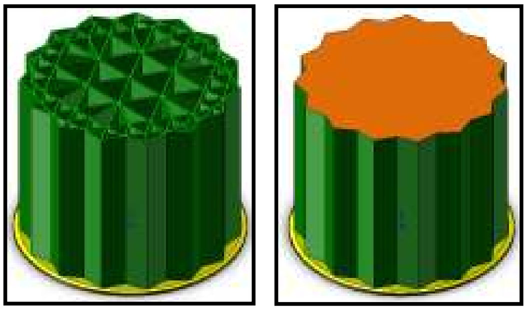


Figure 9. Solid Model Representation for Hibernia Offshore Oil Platform

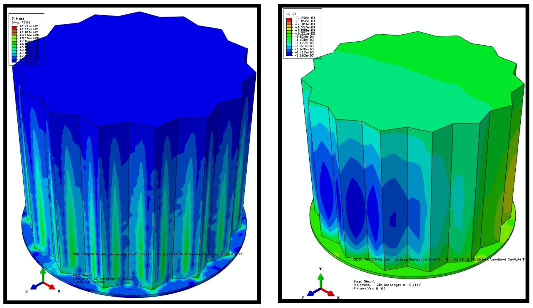


Figure10. Stress and Deformation Distribution over the Offshore Structure

4.2 Stress results output

The main target of this finite element simulation is to predict the locations of the hot stress spots in the offshore structure. Offshore fixed platforms, like the gravity-based structure used for the Hibernia project offshore in Newfoundland; have to be designed to withstand the seasonal presence of sea ice and icebergs and other harsh weather conditions. Figure 10 shows the stress distribution over the simulated offshore structure, the proposed health monitoring strategy will be decided. As expected, it is quite clear that most of the stresses concentration occurred at the middle of the ice-protecting walls that protect the offshore structure from the impact effect of the ice-bergs.

4.3 FBG sensors array layout

Successful monitoring strategy must grantee a continuous record for the sensor readings in comparison with predefined warning values. If predefined warning threshold was reached, then the alert status is automatically activated. Early detection of damage can save lives and costly repairs. The information obtained from monitoring is generally used to plan and design maintenance activities, increase the safety, verify hypotheses, and reduce uncertainty.

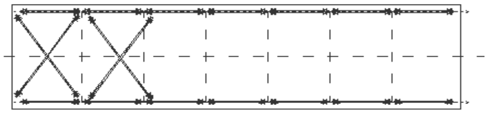


Figure 11. FBG sensor layout

Using long-gauge sensors allow the monitoring of a structure as a whole, so that any phenomenon that has an impact on the global structural behavior is detected and quantified. Based on the FEM results for the Hibernia offshore platform and presented in Fig. 4, the lay out of the FBG is illustrated in Fig. 11 as the sensors are focused in the hot spots for flexural and shear stresses.

5 CONCLUSION

Finite element Simulation was utilized for the determination of hot spot stresses for in offshore platform structures. That enables continuous health monitoring of the structure as well as the capability to detect and monitor locally damaged and overstressed spots. These design guidelines will help design engineers to choose the suitable locations for SHM sensors to optimize the distribution of the FBG sensors in such thick structures. The proposed methods will be used for early detection of structural damage of nuclear structures. Through the use of these methods operators of such structures will be able to maintain safe and economic operation of their facilities. Maintenance costs as well as shutdown cost will be reduced. In addition danger to human life and the environment will be reduced.

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