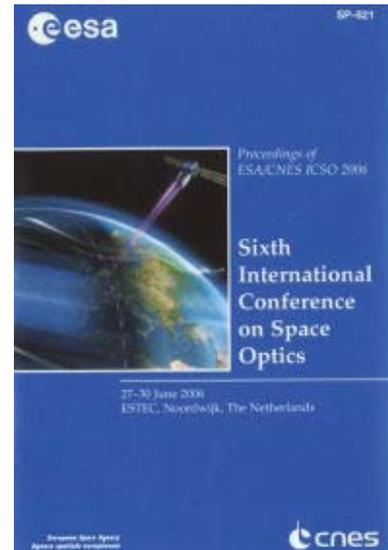


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Vega interstage strain measurements: comparison between conventional strain gauges and fibre Bragg grating sensors

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VEGA INTERSTAGE STRAIN MEASUREMENTS: COMPARISON BETWEEN CONVENTIONAL STRAIN GAUGES AND FIBRE BRAGG GRATING SENSORS

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ABSTRACT

Europe is developing a new generation launcher, called Vega, a small launcher with a capacity to place satellites into polar and low-Earth orbits, which are used for many scientific and Earth observation missions. Its first launch is scheduled for early 2008. Dutch Space is responsible for the development, qualification and manufacturing of the Vega Interstage 1/2. This all-aluminium conically shaped section is designed as a monocoque structure. This subsystem of Vega has undergone its first qualification tests of force loading combined with an extensive programme of measurements (forces, displacements and strains), at TNO in Delft. In parallel to conventional strain gauges Fibre Optic Sensors (FOS) in the form of Fibre Bragg Grating (FBG) sensor arrays, consisting of five strain sensors and one temperature sensor, have been installed on different locations of the interstage. Direct comparisons of the results with conventional sensors during load tests up to several hundred tons are therefore possible. A self-evident benefit of FBG sensors in an array application is that each sensing FBG can have a different Bragg wavelength to reflect. Thus, Wavelength Division Multiplexing (WDM) can conveniently be used to distinguish the different sensing FBG's at the receiving side. First test results from load measurements performed on the Qualification Model (QM) of the Vega Interstage 1/2 are presented in this paper as well as an outlook to future integration of the FBG in this field.

1 INTRODUCTION FIBRE BRAGG GRATING

In the last decades, FBG's have gained increasing interest in sensor applications in addition to their almost conventional use in telecommunication. FBG sensors have been developed for strain, temperature, acceleration as well as pressure measurements. Using a high-speed interrogation system, even shockwave propagation, impact and vibration can be measured. These parameters are of importance for Structural Health Monitoring (SHM) of aerospace structures.

In comparison with other sensors, FOS have a number of advantages: intrinsic safety, there is no electrical component in the sensing point/ area, this excludes fire and explosion danger; immunity to Electro-Magnetic Interference (EMI) and no EM emissions; lightweight, small size, large bandwidth for the detection of high-speed events, ability to be integrated in a sensor network, this includes the possibility to address and to readout a large number of sensors (even for different physical parameters) using a limited number of fibres, and a large operational temperature range. A number of FOS's are already found to be rugged enough for application in the harsh environments of aerospace. ESA's forecasting of FBG applications are mentioned in [1]. The most promising FOS is the FBG sensor. An important additional advantage of the FBG sensor is its independence to variation in signal amplitude like the FM modulation technique used in radio transmissions.

An FBG is a periodical modulation of the refractive index in an optical fibre. This modulation is realized by exposing the optical fibre with a periodic pattern of ultra-violet light. Like a conventional grating, the reflection of a FBG depends on the wavelength. This is described by a simplified form of the Bragg's law in Eq. 1:

$$\lambda_B = 2N_{eff}p, \quad (1)$$

where λ_B is the wavelength of the reflected light, N_{eff} is the effective refractive index of the optical fibre and p is the period of the modulation. A self-evident benefit of FBG's is that each FBG sensor can have a different Bragg wavelength to reflect. This enables the application of FBG sensors in an array configuration, Fig. 1.

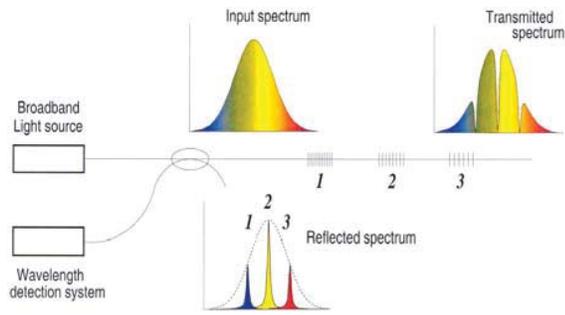


Fig. 1. Wavelength Division Multiplexing FBG sensor array principle.

The FBG sensor system is relatively simple, compact, low-cost and can (easily) be embedded in composite material. It requires simpler wiring compared to conventional strain gauges.

2 ADHESION INVESTIGATION FOR SURFACE MOUNTING

The mounting of the FBG is regarded to be a vital issue for the application of the sensor.

Preliminary tests of FBG surface mounting by just attaching and gluing the fibre to the construction (see Fig. 2) shows hysteresis as shown in Fig. 3. These are caused by insufficient strain transfer from the surface to the fibre, therefore further investigations were performed.

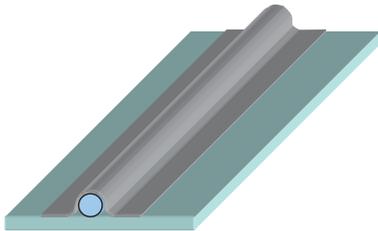


Fig. 2. Preliminary tests with glue surrounding fibre.

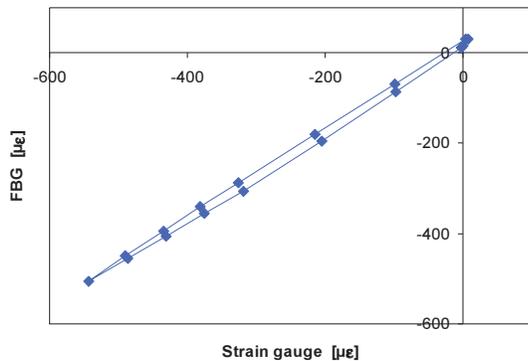


Fig. 3. Non-linearity (hysteresis) demonstrated in preliminary tests.

The procedure for surface bonding of the fibres has been adapted. Instead of putting the adhesive on the surface and then attaching the fibre to it, an area around the fibre is created and filled with glue, see Fig. 4.

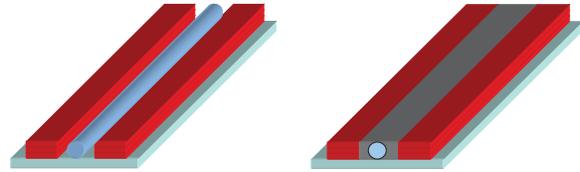


Fig. 4. Optimised procedure for surface bonding of fibres to ensure an improved strain transfer.

12 different glues (compositions) including standard glues for conventional strain gauge mounting are investigated. Based on the mechanical properties and handling, four glues have been selected for further measurements. These four glues are used on a 19 mm diameter steel pipe for FBG surface mounting tests. Conventional strain gauges have been mounted near the location of the FBG's as sketched in Fig. 5 to make direct comparison of the results possible.

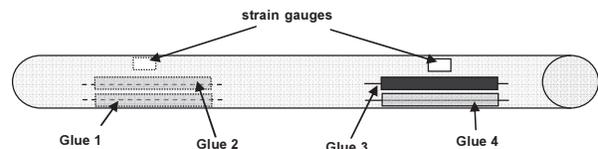


Fig. 5. Steel pipe sketch of sensor position located on opposite sides.

Stress tests have been performed in a dedicated setup at TNO in Delft to a maximum of 100 kN, see Fig. 6.

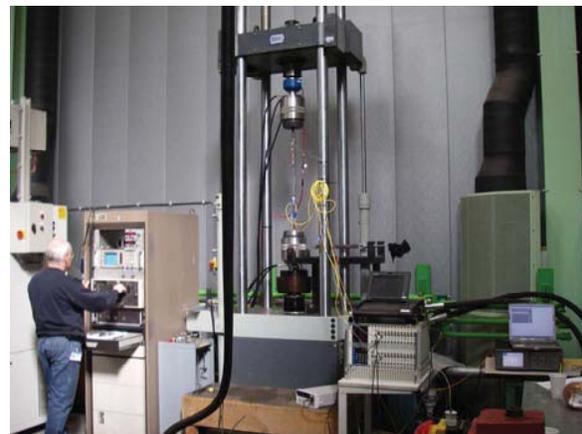


Fig. 6. Setup for stresses up to 100 kN at TNO, Delft.

The results of the stress tests are presented in Fig. 7. The stress is built up linearly from zero to the maximum. The maximum stress level at 100 kN is

maintained for approximately 40 s to verify the effect of creep. The stress is then released gradually back to 0 N. For all four FBG sensors and the two strain gauges the measured strain at the end of this test returns to the begin value of approximately 0 micro strain ($\mu\epsilon$).

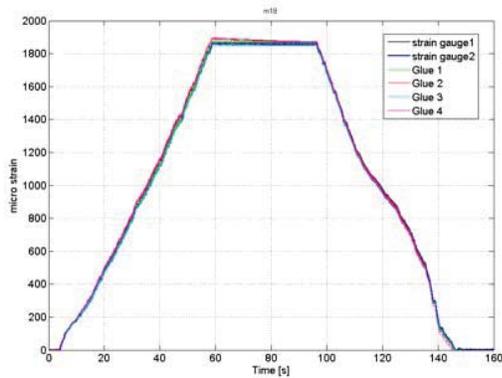


Fig. 7. Micro strain results: FBG and conventional strain gauges.

The difference of the four glues can be observed at the maximum stress level, see Fig. 8. Two of the four tested FBG's (using glue 2 and glue 4) show changes over time in the strain level. The other FBG's, as well as the conventional strain gauges, measure stable strain level. Minor hysteresis remains in comparison to conventional strain gauges with FBG glue 3. Using a scale factor of 1.2 pm/ $\mu\epsilon$ for the FBG's the calculated strain is almost identical to the 1860 $\mu\epsilon$ measured by the conventional strain gauges.

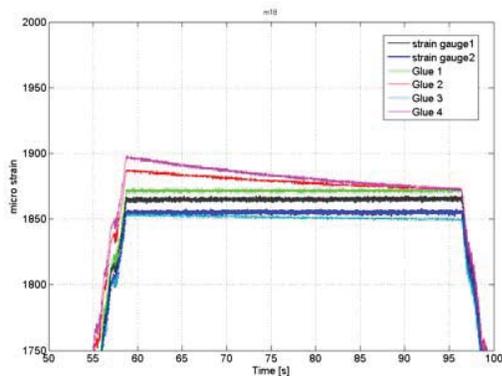


Fig. 8. Results of FBG's mounted by different glues in comparison with conventional strain gauges. Zoom at maximum stress level of Fig. 7.

The noise levels of the FBG and the conventional strain gauge measurement methods in Fig. 8 are demonstrated to be comparable.

The linearity behaviour of the different surface mountings versus the conventional strain gauge is

visualised in Fig. 9 by using data points of Fig. 7. Glues 1 and 3, which are demonstrated in Fig. 8 to have minimum creep, are also found to be most linear to the strain gauge. The correlation coefficient is:

- glue 1: $R^2=1.0000$;
- glue 2: $R^2=0.9996$;
- glue 3: $R^2=0.9999$ and
- glue 4: $R^2=0.9988$.

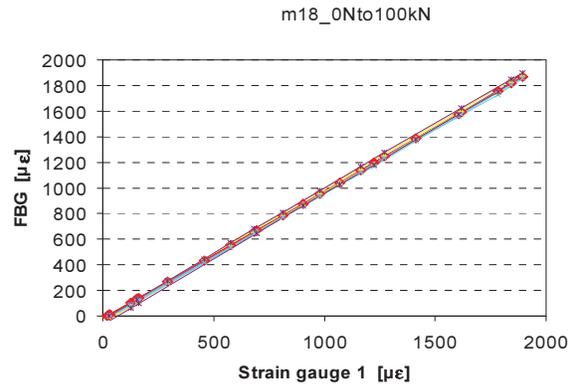


Fig. 9. Sensor linearity of four different glue FBG mountings.

An improvement on the demonstrated preliminary tests by using proper glue and adequate adhesive mounting technology has been realised.

3 VEGA INTERSTAGE TEST SETUP

Vega (Vettore Europeo di Generazione Avanzata), named after the second brightest star in the northern hemisphere, has a capacity to place 300 to 1500 kg satellites into orbit. This four-stage launcher is tailored to carry small scientific spacecraft and other lightweight payloads. A growing number of such satellites are under development or planned worldwide, with Europe expecting to produce 13 such satellites for launch in the coming years. The interstage between the first and the second stages has a forward and aft part to be separated at jettisoning of the first stage during flight.

A dedicated test bench to measure limit and ultimate loads up to failure is based at TNO in Delft, see Fig. 10.



Fig. 10. Vega Interstage 1/2 installed on test bench at TNO, Delft.

Six FBG sensors were installed. To demonstrate multi parameter sensing using FBG sensor array, in the beginning one FBG is used for temperature monitoring. The FBG sensors are placed at different locations in relation to the conventional strain gauges. FBG3 and FBG4 are placed vertically above strain gauge 402B_c, see Fig. 11. FBG2 is located on the same vertical plane as the conventional strain gauge 'TPD', see Fig. 12.

Two detection systems for the FBG sensor array have been used: a commercially available interrogator (Micron Optics SI425) and a high-speed interrogation system developed by TNO (Deminsys) [2, 3]. The Deminsys with a maximum sampling frequency of about 20 kHz can be used to visualise high-speed events during rupture tests, which are planned in the near future. Furthermore, the large quantity of data can also be used to improve the detection limit down to a sub-micro strain level by data averaging.

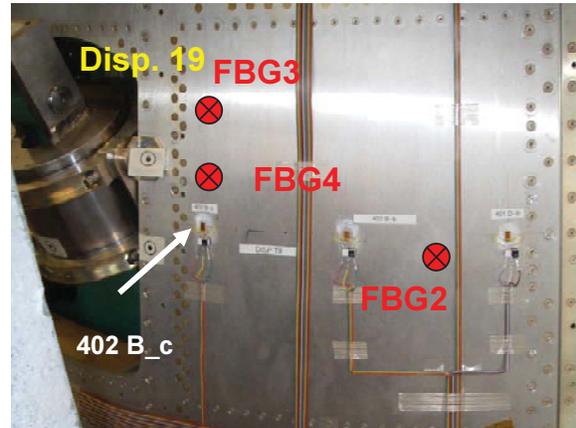


Fig. 11. FBG positions near conventional strain gauges. FBG3 and FBG4 are positioned vertically above strain gauge 402B_c.

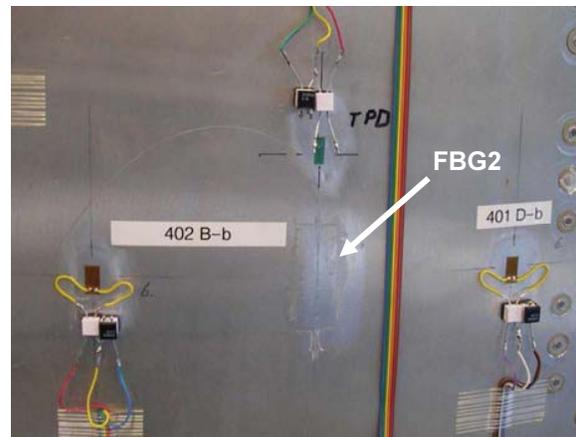


Fig. 12. Conventional strain gauge 'TPD' and FBG2 located on the same vertical plane on the Vega Interstage 1/2.

4 VEGA INTERSTAGE 1/2 TEST RESULTS

The temperature variation of the monitoring point measured by the FBG is limited to less than 1°C during daytime, see Fig. 13.

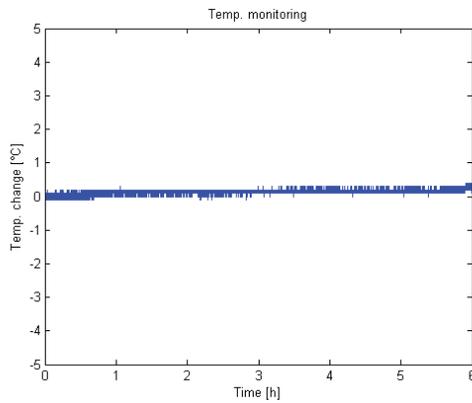


Fig. 13. Temperature monitoring with FBG on VEGA Interstage over several hours.

On and off (eccentric) axis tests were performed on the Vega Interstage 1/2 up to load levels within the designed limit values. The loads are applied in different steps. The measured strain result is shown in Fig. 14. Comparable strains are measured by the FBG sensors and corresponding conventional strain gauges, i.e. strain gauge 402 B_c with FBG4 and strain gauge ‘TPD’ with FBG2.

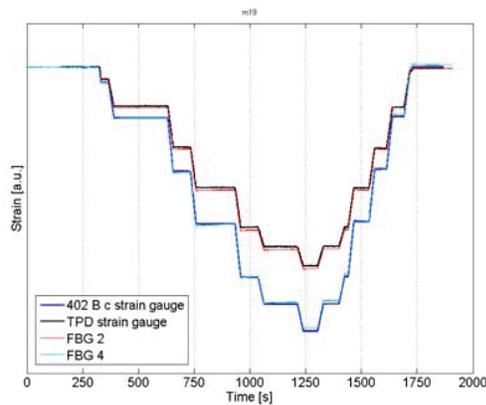
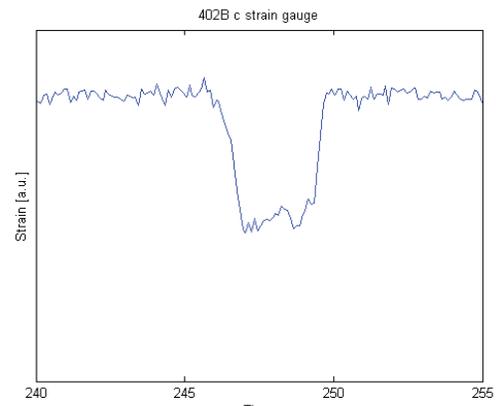
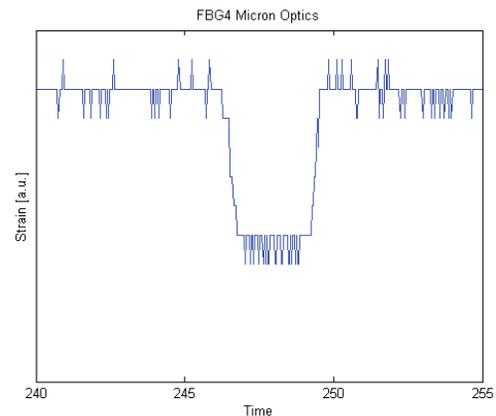


Fig. 14. Limit load eccentric test.

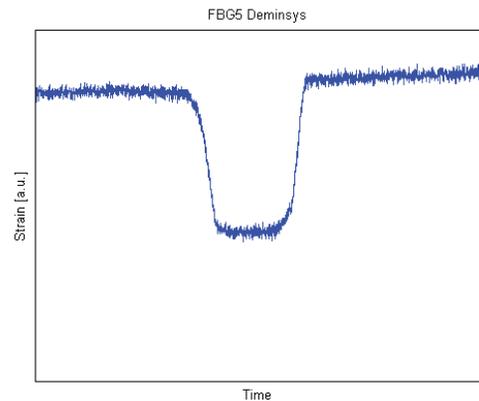
The noise levels and resolution between three different read-out systems can be compared by zooming in a small part of the measured signal. The strain gauge read-out is sampled at 10 Hz. Random noise is visible in the Fig. 15(a). The Micron Optics system operating at 25 Hz (Fig. 15(b)) used for FBG4 shows a higher noise level which is dominated by the last significant bit of the system. The high-speed detection system Deminsys sampled at 190 Hz, Fig. 15(c), shows more detail and lower noise. Further noise reduction is feasible by extra averaging.



(a)



(b)



(c)

Fig. 15. Zoom of Fig. 14. Resolution and noise difference between different systems, (a): conventional strain gauge; (b): Micron Optics system; (c): Deminsys.

5 CONCLUSION AND OUTLOOK

Application of multi-parameter FBG sensor array on the Vega Interstage 1/2 has been successfully demonstrated. The installation is simpler than for

conventional strain gauges due to the limited number of FBG cables in comparison to the wires for conventional sensors. The current sensor array on the Vega Interstage 1/2 is used to measure the strain and the temperature. Investigations on glues and mounting procedures have been performed to optimise the strain transfer from the tested structure to the FBG. The results of the FBG strain sensors match very well with the corresponding conventional strain gauges.

Through the use of proper surface mounting, FBG sensors are found to be useable for launcher subsystems and other space constructions.

A rupture test is scheduled for mid 2006. The high-speed detection system will be used to visualise events such as crack development.

6 REFERENCES

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