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Distributed damage detection of offshore steel structures using plastic optical fibre sensors

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ABSTRACT

In this paper, results demonstrating the potential application of plastic optical fibre (POF) sensors for damage detection of offshore steel structures are summarized. Graded-index perfluorinated plastic optical fibre (GIPOF) was used for crack detection in tubular steel specimens. A high-resolution photon-counting optical time-domain reflectometer (ν-OTDR) was used for interrogating the optical signal. The study will show that the technique adopted in this study is able to determine the position of the crack in the host structure with high accuracy and repeatability. The technique was also found to be capable of monitoring crack growth in the steel specimens used based on a serpentine sensor configuration.

1. Introduction

Offshore platforms, in general, consist of a superstructure and a substructure. The substructure, typically built using steel tubular jackets, are fabricated by joining tubular steel members together using welding and then pin-jointed to the seabed with steel piles. In a complex structure such as that of an offshore platform, there are many potential failure hot spots, which may result from fatigue due to cyclic stresses generated by sea waves. Cracking in the steel tubular members may occur at locations of high stress-intensity due to the physical discontinuities at the intersections of brace and chord members. At welded joints where abrupt changes in geometries are expected, cracks may initiate and propagate under cyclic load. Stress concentration could be as high as twenty times that of continuous non-welded sections at certain critical sections [1–3]. Therefore, detecting and monitoring such cyclical stress-induced damage e.g. crack growth, would give an objective measure of the rate at which the crack is propagating and therefore the level of urgency for repair work to be carried out to arrest the crack. In addition, there has been increasing demand for documentation of safety in the offshore industry by classification societies to carry out inspection and structural checks. The need for an effective structural integrity damage detection system in offshore structures has indeed been highlighted in many reports available in the public domain [4,5].

Over the past few decades, the concept of structural health monitoring (SHM) has emerged as an attractive but challenging area of research [6,7]. At the most elementary level, an SHM system requires a sensing system capable of obtaining specific information from which the health of the structure can be inferred. While there are many sensors available, optical fibres offer unique advantages due to their insusceptibility to corrosion as well as their non-flammable and non-conductive nature. Their insensitivity to electromagnetic interference and long term stability are some of the differentiating features compared to other electrical-based sensors. Another significant advantage of optical fibre sensors is their potential for distributed monitoring along a single fibre while offering damage detection capability with high spatial-resolution, allowing large structures to be reliably monitored. This is a significant advantage over placing a large number of individual sensors on the host structure, requiring immense amount of electrical cables to be linked up. Besides being capable of true distributed monitoring capability, optical fibres sensors have, over recent years been demonstrated to be capable of monitoring a variety of parameters including measurement of strain, load, displacement, the extent of bio-fouling, detection of moisture and the presence of cracks [8–10].

Polymer-based optical fibre has, in recent years, been attracting significant amount of attention for sensing applications [11,12]. Plastic optical fibre (POF) offers ease of handling, termination and

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coupling compared to glass optical fibre. Although glass optical fibre of the same size could be used in view of its potentially higher crack detection sensitivity, it has to be in its bare form i.e. with its protective plastic jacket/buffer/coating removed in order to exploit the sensitivity of the glass fibre. The fibre will need to be attached directly onto the structure over its entirely sensing length for distributed monitoring – the use of which requires significantly more care during installation to prevent accidental damage to the bare fibre since bare glass fibres are susceptible to fracture. In addition, the smaller bending radius achievable with POF and ease of cleaving provide further flexibility and incentive which led to the adoption of POF as the medium of choice in this study. POF-based sensors, in general, offer good chemical resistance and are able to operate in a relatively wide range of temperatures (−20 °C to 90 °C). POFs, with their large core sizes (diameters from 0.25 mm to 1 mm) are commonly used in their development for structural health monitoring sensing work. The core of the fibre could be made from poly(methyl-methacrylate) (PMMA), polycarbonate (PC), polystyrene (PS) and more recently poly(perfluorobutenylvinyl ether) which is also known as CYTOP [13].

OTDR is a well-known technique in telecommunication for fault analysis and crack detection in silica fibres. OTDR sensing relies on the monitoring of the backscatter light in an optical fibre following the launched of a short optical pulse at one end of the fibre. The backscatter signal is recorded as a function of time which is then converted to a distance measurement. Perturbations, such as strain or defects along the length of the fibre, will result in either a Fresnel reflection (appearing as a peak in the OTDR trace), or loss in the backscatter signal at the location of the perturbation (termed as an event). The ability to detect the very low intensity light levels and high detection speed in *photon-counting* ν-OTDR has rendered it possible to achieve a high level of spatial resolution not achievable using standard OTDRs. The use of graded-index fibre in conjunction with ν-OTDR also reduces the modal dispersion encountered in step-index PMMA fibres and hence allows monitoring over a longer distance in such fibres [14–16].

Taking advantage of the high strain measurement capability of standard PMMA POF, a strain sensor consisting of a free section of a length of POF secured at its two ends has been demonstrated to be capable of distributed strain monitoring using OTDR technique [17]. The sensing principle involves measuring the increase in the backscatter level in a section of the POF when the fibre is stretched [15–18]. This involves converting the change in the intensity of the backscatter to strain values via a fibre-dependent strain-optic factor. However, some technical difficulties associated with the technique have been highlighted by the authors which include non-linearity of the strain-optic factor at higher strain levels (>16%), material relaxation and hysteresis under cyclic load. To overcome the non-linear response, the authors have applied a cross-correlation algorithm and the method was found to be effective [16,17]. While the technique has been shown to be highly encouraging, extraction of the strain information from the OTDR trace requires additional post-processing of the raw data. The monitoring of strain to infer damage in structure proposed is generally more resource intensive and requires rigorous computational work compared to other more direct approach of damage detection such as monitoring for the presence of cracks in the structure. Moreover, in the former approach the fibre must experience strain level of the order of 1% or more in order to induce a change in the backscatter level [17], excluding its use in applications where structural members exhibit small strain responses prior to failure such as in the case of a brittle fracture.

The alternative approach to monitoring structural damage have been proposed using PMMA standard POF [19,20] and this may reflect a more direct damage detection route i.e. by detecting the presence of damage itself (e.g. cracks) as the parameter of interest. In applications where the presence of cracks at load-bearing locations could lead to progressive failure of the structure, the ability to detect them early, and in a straightforward manner is evidently desirable. There are advantages associated with each of these health-monitoring approaches and depending on the requirements of the application at hand, users ought to be clear on their expectations and damage detection needs. Clearly, a combined approach may be the way forward in developing a comprehensive and practical solution where a structural health monitoring system is to be applied.

This paper investigates the possibility of using the OTDR technique in conjunction with graded-index (GI) POF to detect damage in steel tubes by way of detecting the presence and locations of cracks. By comparing the final OTDR trace with the original trace of undamaged fibre, it may be possible to infer damage of the host structure with information of the location of the damage. In addition, by arranging the POF in a specific configuration, the study aims to examine the feasibility of using the technique to monitor crack growth. The intention of this study is to gain some practical experience in the application of GI plastic fibres with the use of a high-resolution optical time-domain reflectometer (ν-OTDR) for crack detection in tubular steel specimens for potential application in offshore structures.

2. Experimental programme

2.1. Experimental methodology

The objective of the study was to observe the response of the POF and to assess its potential as a distributed sensor for crack detection in tubular steel structures under a three-point flexural loading condition. The study also aimed to assess the ability of this technique to monitor the propagation of a crack. In the field, cracks are often initiated at locations of high stress intensities and where cracks have initiated, they grow under fatigue loading leading to the eventual collapse of the structure. In this study, the crack growth in the specimen was initiated via a pre-crack introduced to the specimen prior to the loading test. The steel tube was loaded under flexure and the crack growth was observed closely throughout the test. To assess the ability of the technique to detect crack and monitor the crack growth, a serpentine fibre configuration was attached to a short steel specimen measuring approximately 0.45 m. A three-point bend set-up was used in the study as shown in Fig. 1.

In the set-up used, the crack propagated upwards and approached the first segment of the POF fibre. The idea used in this study is straightforward and relies on the fact that when the crack propagates and intersects the POF sensor, a change in ν-OTDR trace is expected, which could provide information regarding the crack. In the event of a POF fracture resulting from the crack front intersecting it, the emergence of a new peak in the ν-OTDR trace would provide information on the location of the crack site on the steel specimen since the new peak would correspond to the location of the fracture on the fibre. During the test, the loading was applied in a series of steps and stopped intermittently to allow the ν-OTDR data to be recorded. The loading was applied until the crack propagated through the entire segments of the POF sensor. The ν-OTDR instrument from Sunrise Luciol was set to monitor the backscatter signal from POF sensor continuously and update the trace of the backscatter signal in quasi-real-time mode. The measurement time of the ν-OTDR was set to 1 s without averaging and the light source selected was centred at wavelength of 658 nm.