Stress Monitoring of Civil and Mechanical Engineering Infrastructure

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Abstract
Structural Integrity Monitoring is a rapidly growing science and practice which promises in the future to measure and record every shudder and twitch within the lifetime of future structural components. Indeed, structures will undoubtedly possess nervous systems which will sense and instantly communicate loading and damage information; however, it is timely to stand back and consider what is required from such systems before we drown in yotta-bytes of monitored data.

The electronics industry is rapidly developing clever wireless data transmission and more efficient storage methods, with increased sampling frequencies and multiplexing technologies which can distract even the most focused Civil or Mechanical Engineer. Stress measurement and monitoring is more complex than traditional NDT which considers defect and crack detection, but if understood properly can in some ways be much simpler and promises safer and better optimised structures.

The paper reports several case studies of stress monitoring in Rail applications and of Steel Structures using Stress Memory Technology and will discuss how stress monitoring systems might be evaluated in terms of reliability and value.

Introduction
The idea behind Stress Memory Technology [1, 2] is simple. Each sensing device is self-contained and passively senses and records the occurrence of pre-defined structurally significant events. It is permanently attached to the surface of engineering structures and acts as a local "Memory". It does this by sensing micro-strain on the surface of the host structure, analysing the monitored strain for structurally significant events and records the occurrence of pre-programmed events. It only communicates its information when required. A Stress Memory System consists of one or more Stress Memory Units and a data reader/computer.

By definition Stress Memory Units are based on monitoring the primary cause and effects of progressive flaw development rather than to directly monitor the development of flaws themselves. A crack/flaw inspection/monitoring system having high POD (Probability of Detection) and POS (Probability of Sizing) attributes can at best tell the existence, type, location and size of the flaw at any point in time. It cannot however, give any indication of whether or not a flaw is likely to develop. On the other hand, stress-monitoring systems can identify components, which by the nature of their stress history are more likely to contain stress-related flaws. The Stress Memory Unit is wireless and self-powered. It may be interrogated by an electronic scanning device or programmed to transmit its data. The stress memory device has been conceived for long-term operation (ideally several years) without user intervention. Ideally the Stress Memory System will have a similar life to the design life of the host structure.

Long wires used with analogue electrical and fibre optic strain measurement systems are the cause of signal deterioration and require signal boosters and/or conversion to digital form. The Stress Memory Unit is completely wireless, thus eliminating sources of error associated with wired systems. A major advantage is that the unit itself carries out signal conditioning and analysis meaning that its output can be read and easily understood by non-specialists. Stress Memory Technology has been successfully applied in the rail industry by Network Rail, AMEC SPIE Rail UK Limited and Jarvis Rail [3 - 7] monitoring Stress Free Temperature in Rails and stresses in Points. The following sections briefly describe these along with a stress monitoring application during construction of a new building. This is followed by a discussion of how stress monitoring systems might be evaluated in terms of reliability and value.

Measurement of Rail Stress Free Temperature (SFT)

Continuous Welded Rail (CWR) needs to be installed under tension to protect it from compressive buckling stress as the rail temperature rises in summer. By pretensioning rails the thermal expansion induced compressive stresses are significantly reduced so that the track ballast, sleepers and fastening components, can safely contain these. Conversely, the pretension level must be optimised so that it does not contribute to rail breaks under excessive tensile stress when rails contract in low winter temperatures. Track buckles and rail breaks are both potentially dangerous and monitoring of rail stress is crucial to the safety of the railway.

The Stress Free Temperature (SFT) or Neutral Temperature is the rail temperature at which the rail is the same length as it would be in an unrestrained state and at which, therefore there is no thermal force present. The rail is pulled by hydraulic rail tensors to achieve a SFT of 27ºC (in the UK) when the temperature is outside the range 21-27ºC. Stresses in rails change over time due to deterioration of tracks, the condition of track ballast, traffic density and type, track maintenance, and weather conditions.

Figure 1: Rail SFT Monitor

The SFT Monitor shown in *Figure 1* above is an electrical resistance strain gauge based system. The unit has a 2.35 Amp Hour nominal battery capacity and 32 MByte data storage. The life of this depends on the sampling frequency and length of time in communication mode. As an illustration the unit sampling continuously at 0.5 Hz has a battery life of 19.24 weeks and memory storage capacity of 52.78 weeks.

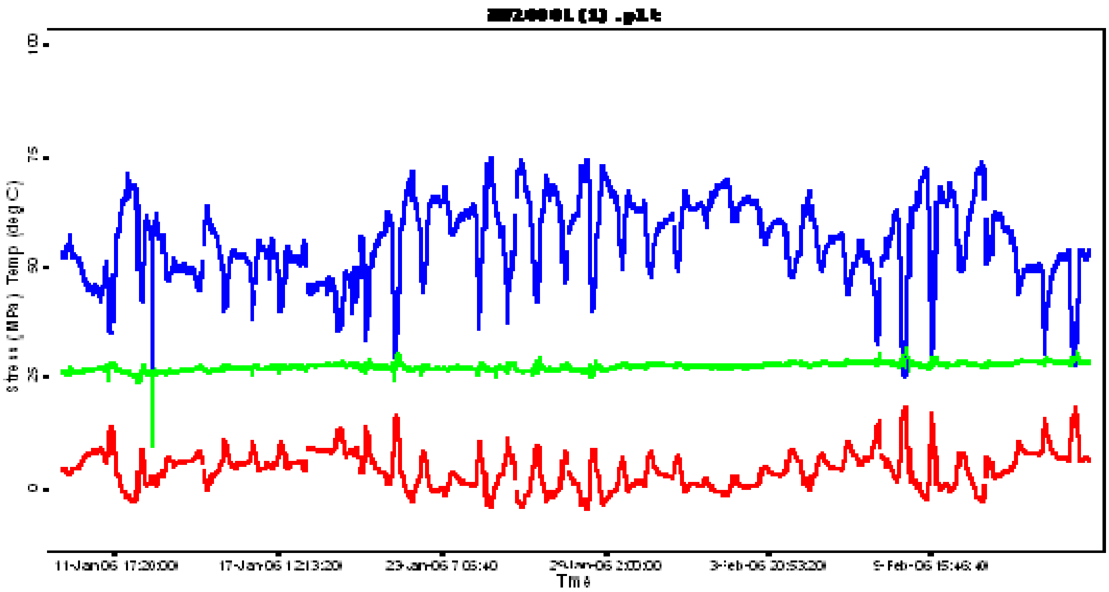

Figure 2: SFT Measurements at a mining subsidence site (37 days)

Figure 2 shows the results from an autonomous unit monitoring temperature, stress and stress free temperature between 9 January and 15 February 2006. The red line shows the temperature fluctuations between day and night, the blue line the associated rail stress and the green line the calculated stress free temperature (SFT). Rail temperature during the measurement period ranged from -9.0˚C to +24.4 ˚C, average rail temperature over the period was 5.1 ˚C. In addition to regular passing rail traffic the period had regular snow, frost and heavy rain.

The purpose of this application was to monitor rail SFT only and rather than collect all stress/strain information in the rail the unit only measured longitudinal stress on the rail neutral axis. In this way the shear and bending stresses due to passing trains were not measured and so did not need to be filtered out. In addition, the relatively slow thermal cycle meant that there was little point in sampling at a frequency greater than 0.5 Hz allowing for a battery life of 120 days despite the cold weather conditions. The elimination of wires and the siting of the electronics in a Faraday Cage at the point of measurement gives very good results with no spurious data or significant scatter.

Stress Monitoring of Railway Points

Another Railway application is the integrity monitoring of Railway Points (switches). A correctly fitted backdrive (supplementary drive) will reduce the risk of premature wear and failure on long switches. They achieve this by holding the planed length of the switch rail up against the stock rail, and assisting the point motor/clamp-lock in moving the switch rails across. However, incorrectly fitted drives can accelerate wear and reduce system capability, leading to component failure, points failures and delays. In order to improve the set-up of conventional (mechanical) backdrives and the diagnosis of faults, it would be advantageous to provide technicians with a means of assessing the set up of the backdrive. Development of this tool requires an improved understanding of the distribution of stresses/forces in backdrives and the changes that occur between a satisfactory set-up and a poor set-up. It is necessary to find a means of measuring these forces easily and reliably, with the information provided to the technician in a readily understandable form. This section reports stress measurements made on railway points (below) and highlights the relevant issues associated with the application.

Figure 3: Full depth CV Railway Points

Figure 3 above shows the Points used for the measurements. This was a Switch type 113A Full depth, “C” type, operated by a HW style machine. There were three stretcher bars, two un-drilled and clamped. Rails were observed to be heavily worn with slight crippling of the right hand switch rail. Some juddering of switch rails was observed during movement suggesting some wear to the drive mechanism. Otherwise, the switch appeared to be in good condition. With the points closed and locked in the normal position, a small gap (2-3 mm) was apparent between the switch and stock rails between the 1st and 2nd stretcher bar. Stress Memory Units were attached along the longitudinal axis of the front drive rod, rear drive rod and middle stretcher bar. *Figure 4* below shows a Stress Memory Unit attached to a one of the stretcher bars.

Figure 4: Railway Points Monitor

Figure 5 shows the results of a points switching operation sampling at 100Hz.

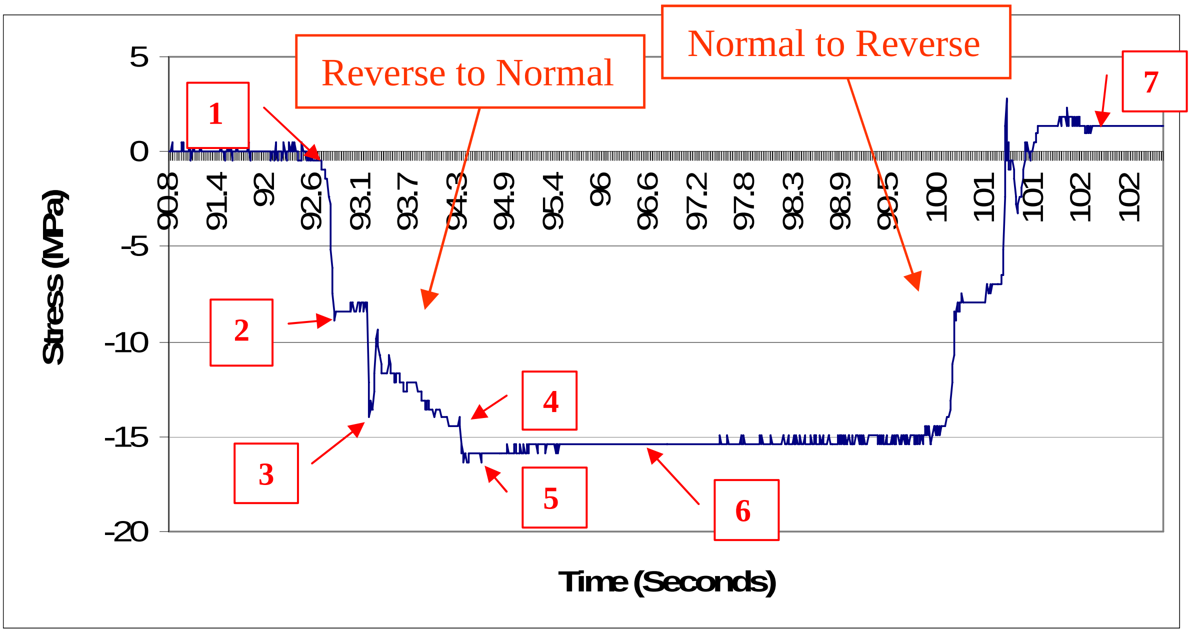

Figure 5: Switching Stresses on front drive rod sampling at 100Hz

It is useful to relate *Figure 5* to movement of the switch. The sequence starts with the points reversed.

1-2	the point motor starts up & unlocks the points (all activity taking place within the point machine)
Plateau after 2	the drive rod starts to move, taking up the slack in the system and the free movement on the drive rod
3	The drive picks up the switch rail (from the reverse position)
3-4	The points move from reverse to normal position
4	the switch rail completes its movement and the switch rail comes into contact with the stock rail (normal position)
4-5	the points are locked and the motor shuts off (as per the plateau after 2), it is likely that the system "relaxes" slightly hence the slight change in stress after point 5
6	The steady state load
6-7	the difference between the two steady-state loads

The sequence was repeated sampling at 50Hz (*Figure 6*) and at 20Hz (*Figure 7*). It can be seen that the key features described above are clearly visible at 50Hz but are less clear at 20Hz.

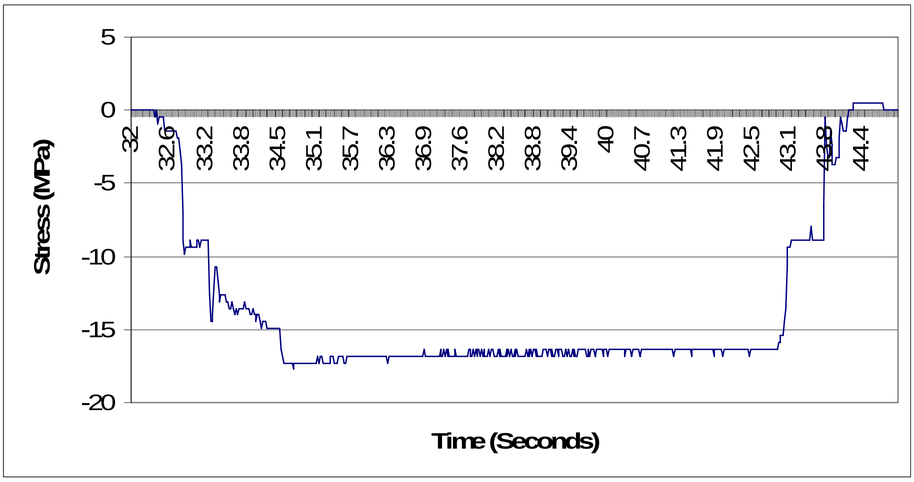

Figure 6: Switching Stresses on front drive rod sampling at 50Hz

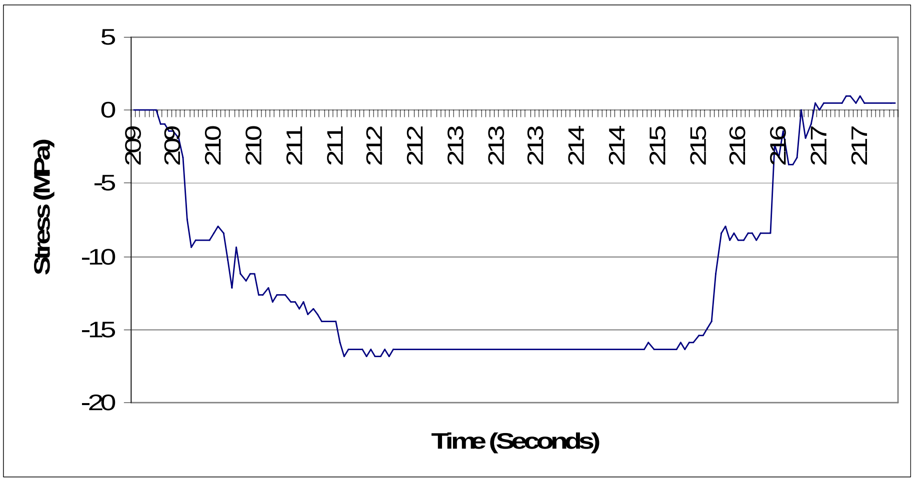

Figure 7: Switching Stresses on front drive rod sampling at 20Hz

The actual sampling frequency however can be much less if for example only the steady state switching load is required. This illustration shows that interesting but possibly unnecessary data is collected with higher sampling frequencies, the resolution of the stress monitor is also impressive and lack of interference is noteworthy. The trial site was in close proximity to 25,000 AC overhead power lines and conventional laboratory monitoring equipment suffered significant interference.

Monitoring Stress during construction of a large Office Block

This section reports the monitoring of a structurally sensitive location during construction of an eight storey steel frame building in Central London. This is shown in *Figure 8* below. Several Stress Memory Units were attached to various parts of the steel frame monitoring stress for different reasons. The unit concentrated on here was attached to a temporary diagonal truss member. The truss was to be removed later in the construction when all columns had been installed. There was therefore some concern the truss would transfer load adequately. *Figure 9* shows the monitored data for a three month period during construction. Early in the record the stepped compressive stresses are apparent and coincided with various floors being added. The unit was removed for several weeks as it was required elsewhere then reinstated.

Figure 8: Steel Frame Multi Storey Office Block

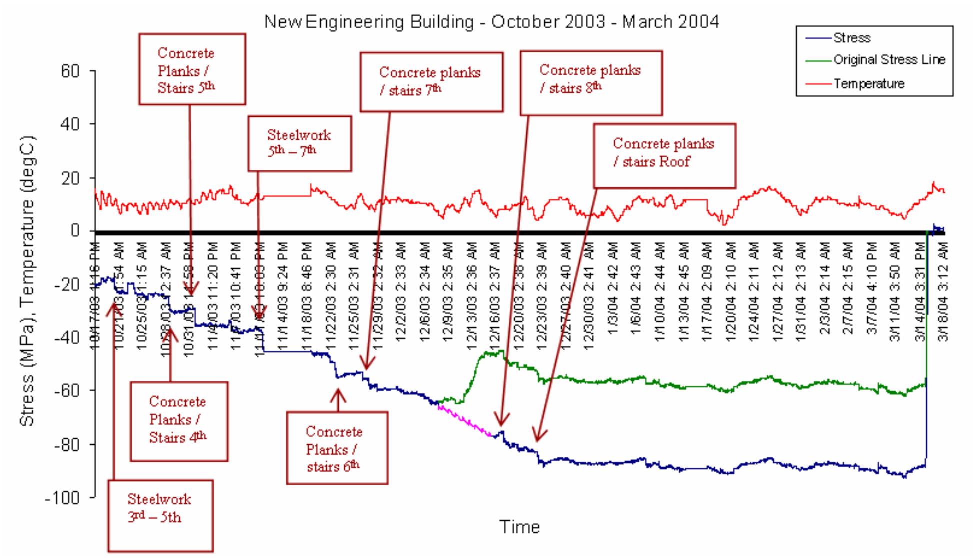

Figure 9: Stress Monitoring Record on Steel Truss over five month period

This is a good example where periodic monitoring of such a relatively slow operation becomes possible. In early December there was a redistribution of load that alerted the contractors and surveyors that there was a potential problem with the truss. It was later discovered that the bolts used had been designed to contain tension and not shear. The bolted joint had slipped in shear causing redistribution of loads. Monitoring of stresses allowed remedial action to be taken before permanent damage occurred.

Discussion

Structural failure is generally a slow progressive process whether by fatigue cracking, wear, corrosion or by some other cumulative damage mechanism. Structural Integrity Monitoring allows trends to be observed whereas traditional NDT can generally only characterise

Fatigue Damage

Stress information – fatigue

Rainflow cycle counting

Weighted average stress range

Reliability and accuracy

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