Structural Monitoring of the Restoration of Titanic's Dry Dock

Myra LYDON[1], Su TAYLOR[1], C. DOHERTY[2], S. GRATTAN[3], Paul CAMON[4]
[1] School of Planning, Architecture and Civil Engineering, Queen's University Belfast, NI
mlydon01@qub.ac.uk s.e.taylor@qub.ac.uk
[2] Buro Happold, Dubai, UAE [3] Sengenia Ltd, Lurgan, UK [4]McLaughlin & Harvey Ltd

Abstract. Belfast landmarks inextricably linked to the story of the Titanic are now opening to the public. Thompson Dry Dock was built in 1905 especially for the final fit out of the Titanic and her sister ships and it is currently being restored as part of the 'Thompson Titanic Trail'. The lock gate and dock were last used in 2001 and were deemed unsafe for use due to the corrosion that has occurred over the last 100 years in the steel that forms the lock gate structure. This has prohibited safe access to the floor of the dock. Restoration is underway to ensure that the dock can be opened safely as a tourist attraction in this the centennial year of the Titanic. This paper present some of the results of structural monitoring of the steel work which ensured the safe transfer of loading from the original lock gate to enable construction of a new bund. The real time monitoring during dewatering ensured the safety of staff working inside the cofferdam and integrity of the transfer structure through the highest loading conditions

1. Background to Thompson's Dry Dock and Lockgate

Thompson's Dry Dock (Figure 1) provides a true reflection of the epic scale of the shipbuilding industry in Belfast and is a dominant feature in the Titanic Quarter. The dock was first opened by Belfast Harbour Commissioners in 1911 when the 259.1m (850 feet) long Thompson Dry Dock was the largest in the world, taking ~500 men over more than five years to build, at an equivalent cost in today's money of £50m. The dock was used to check and paint the Titanic's hull, fit the propellers into position, install the boilers and to apply some of the final fixtures and fittings. Named after the BHC Chairman of the day, Robert Thompson, the dock could be drained of its 24 million imperial gallons of water in l00 minutes using the huge pumps in the adjacent Pump-House. Both the dock and pump house are masterpieces of Edwardian engineering and provide great inspiration for the Science Park's hi-tech occupants who are reclaiming Queen's Island's as a centre for innovation.

The lock gate was a travelling caisson and as it was constructed in the early 1900's it coincided with the move from wrought and cast iron to steel after the advances in the Bessemer process for controlling the carbon content in iron. The steel used was the best material of the day but equivalent to low grade mild steel today. The gate is a hollow structure with internal spanning members and is divided into two internal horizontal compartments, the lower one being approximately three times the size of the upper. The frame of the gate is made of riveted steel plates (similar to those in the Titanic). Riveting was reaching the end of its life cycle; it had been common in wrought iron structures but has been replaced by welding and bolting

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Figure 1: Thompson's graving dock and lock gate

The plates of the caisson were designed for the varying water pressures and ranged from 6/20' (7.5mm) to 25/40' (15.6mm) in thickness [1]. All these plates are lapped together, the seams being single and the lap butts double riveted throughout. The caisson internal framing is composed of steel angle bars and plates. The frame consists of angle bars 4"x3"x0.5" (100x75x12.5 EA) at 18" (450mm) centres; and the vertical and bottom corner angles 4"x4"x0.5" (100x100x12.5 EA). The steel frames extend from the top of the bottom corner angles to the underside of the water tight deck, and from the top of the water tight deck to the underside of the rail. The gate could be opened in 5-7 minutes when powered by a three cylinder brass hauling engine. The seal between the gate and the dock wall is made of greenheart wood. Greenheart wood was used mainly in Europe for underwater applications such as pilings for wharves, bridges and ships and there has been signs of deterioration in the seals.

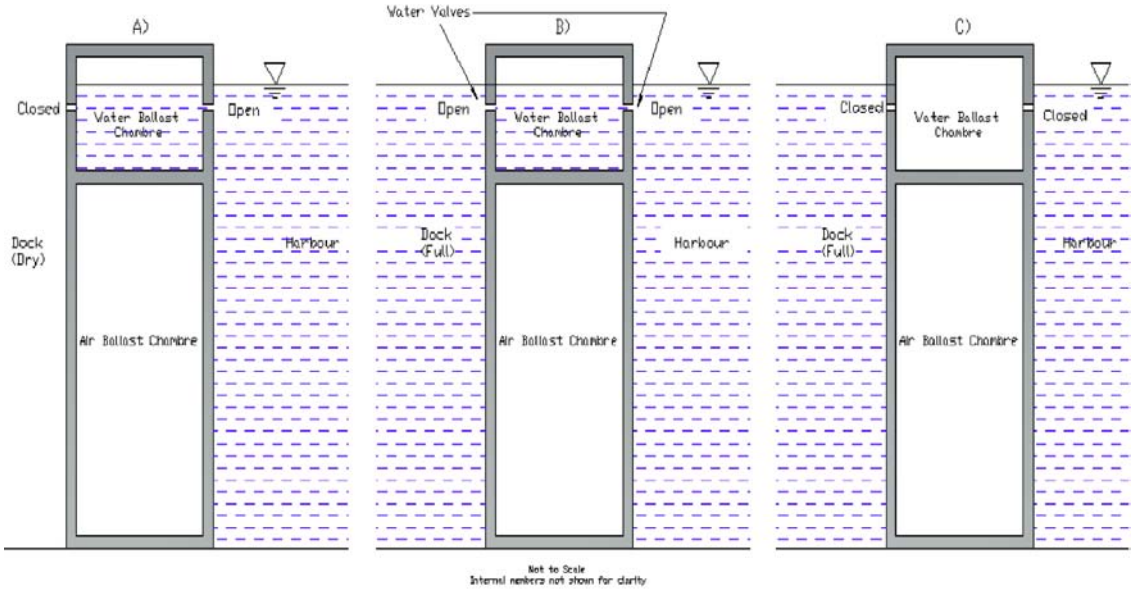

Figure 2: Simplified drawing of Thompson's graving dock lock gate operation

The dock is kept dry when not in use, that is, the lock gate is kept closed and in position. As a structure the gate is divided into two compartments where the lower larger compartment is an air chamber to facilitate buoyancy when opening and the upper compartment is a water ballast chamber and enables the position of water valves at lower pressure as shown in simplifies diagram in Figure 2 [2]. The air chamber is constantly kept dry but has a high humidity level. the water ballast chamber can be wet or dry depending upon whether the water valves on either side of it are opened or closed. Both of these compartments are separated from each other by an internal steel plates.

2. Corrosion of Thompson's dock lock gate

The maximum height difference between low and high water in Belfast Lough (marine) is 3.9m but more generally about 3m, and this has enabled daily wetting and drying cycles to a large part of the steel structure. The plating elements and the internal structure exposed to this tidal wetting and drying have suffered from severe corrosion and corrosion rates in marine environments are much higher in the presence of oxygen that is the tidal zone. These levels of corrosion are also affected by the composition of the water and seawater in can be severe, due to the abundance of salt in a wet and airy position [3] Where steel is depassivated, that zone acts as an anode and the rest as the cathode (Fig. 3). The oxidation of steel requires their presence and also an electrical connection between the anode (positively charged region of the surface) and the cathode (negatively charged region of the surface). Electrons flow from the anode to the cathode and iron atoms in the anode area are converted to positively charged iron ions (Fe2+). These ions react with the hydroxyl ions (OH-) in the electrolyte (the wet concrete) and form iron oxide (or rust). An electrolyte is used to transport the electrons from the anode to the cathode. A survey of the gate [4], using a team of divers, showed that the majority of the corrosion that had taken place was in the Wet Bulkhead (top section) of the gate, specifically near the lowest astronomical tide (LAT). It was estimated that over 50% of the steel plate thickness had depleted in some areas and as a temporary measure steel props were used to support the frame. The different tidal levels upon the gate are as shown in Figure 4, ranging from the Highest Astronomical Tide (HAT) to the Lowest Astronomical Tide (LAT). Chart datum is used when dealing with these tidal levels and in Belfast Chart Datum is the LAT. The difference between chart datum and Ordnance datum in Belfast is -2.0m, therefore the LAT is -2.0m OD

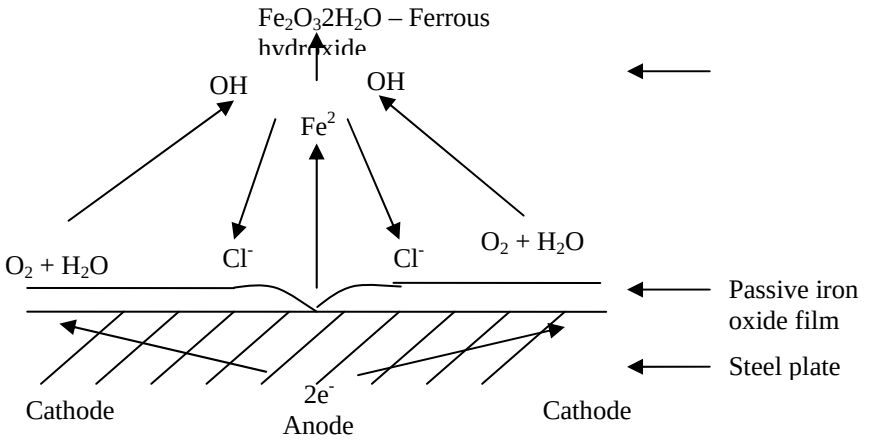

Figure 3: Corrosion model [5]

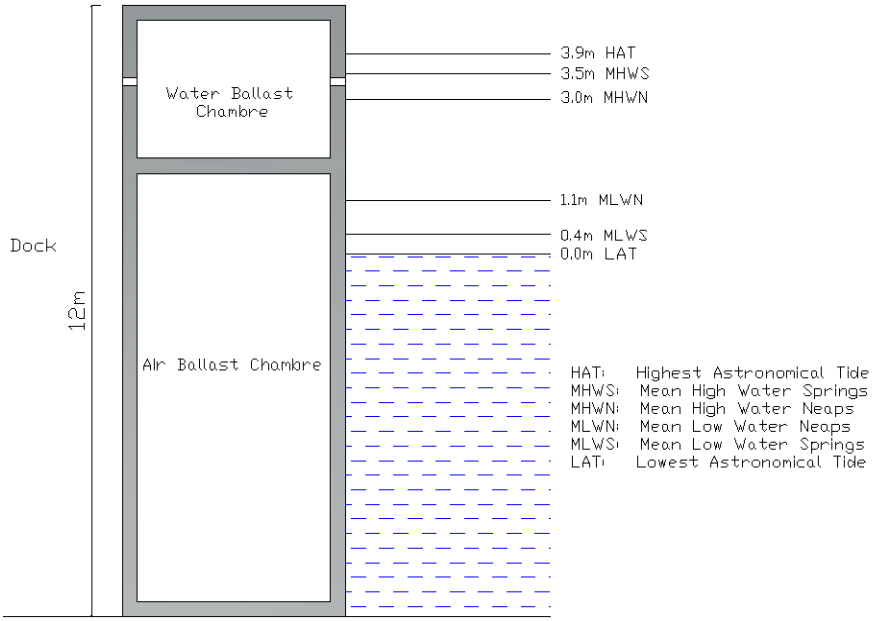

Figure 4: Tide levels and loading on the original dock structure

The original plate thicknesses range from 11.4mm to 15.9mm and a survey of the more recent steel thickness results for both the dry and wet bulk head showed that the gates had suffered severe corrosion in most places the steel plate thickness had been reduced by 20% and in some areas it is from 35-50% and the integrity of the structure was severely in doubt. It was at this time that the Science Park sought funding to provide a permanent solution for the renovation of the gate.

3. Restoration of the lock gate

Restoration works on the Thompson's Dock and the Lock Gate are ongoing at the time of publication and due for completion December 2012. The original lock gate is currently enclosed in a temporary cofferdam formed from sheet piles to enable the construction of a permanent bund across the entrance to the dock (see dotted line on figure 1). This will ensure that the tidal pressures from Belfast Lough are safely contained by a new durable structure whilst allowing safe access to the Thompson's Dock and the Lock Gate for tourists. Figure 5 shows the support structure which were needed to transfer water pressure loads from the sheet piling to the dock walls without affecting the original lock gate structure and enabling the safe construction of the new bund structure.

As the construction is still ongoing, the results presented in this paper are part of an ongoing monitoring programme until the new structure is in place.

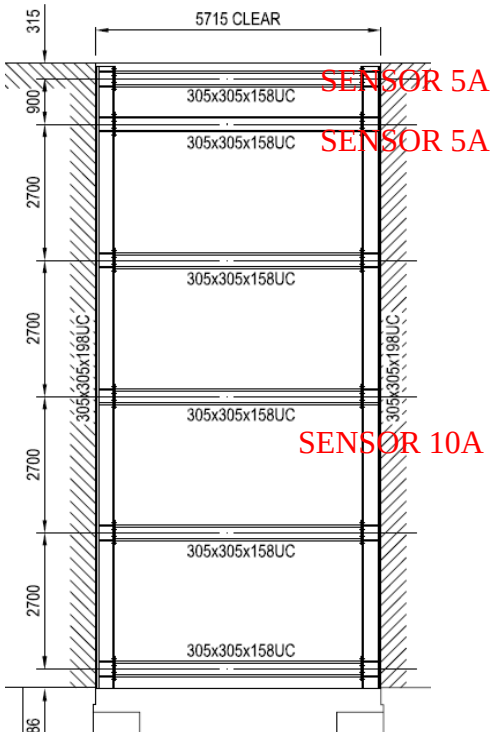

Figure 5 : Transfer structure

4. Monitoring regime

4.1 Optical strain sensors

Optical sensors, namely Fibre Bragg gratings (FBGs) are now well established for the measurement of strain, temperature, and other parameters such as pressure. The sensing signals from FBG are wavelength encoded, making them well suited to multiplexing and enabling measurements of multiple sensors along a single cable and single network. FBG strain sensors show advantages over other commercially available strain sensors due to the intensity-independence of the measurement signal. Furthermore, FBGs are small and lightweight, electrically passive, immune to electromagnetic interference (EMI) and, most significantly for this application, are resistance to corrosion in a marine environment [6]. An additional advantage is the ability to combine FBG's to compensate for temperature induced strain changes. A number of techniques have been reported, such as hybrid Bragg grating/long-period gratings [7], dual-wavelength superimposed gratings [8], dual-diameter FBGs [9]. FBGs super-imposed with polarization-rocking filters [10] FBGs combined with erbium doped fibre amplifiers [11], the use of long-period gratings [12] FBGs inscribed on the splice joint between two different fibres [13] and a chirped Bragg grating fabricated in a fused fibre taper [14]. The key feature of a suitable FOS is to discriminate between strain and temperature thus providing accurate strain data while providing enhanced mechanical resilience during installation and in use measurement.

The os3155 is a rugged strain gage with integrated temperature compensation (Fig 6). Both strain and temperature compensation measurements are based on FBG technology. The FBG has been optimized for outdoor installations on steel structures and the carrier steel holds the FBG in tension and protects the fibre during installation. As there are no epoxies holding the fibre to the carrier, long-term stability is ensured. The benefits of this approach include both more accurate temperature compensation (since the strain and temperature measurements are made in close proximity) and lower-cost installation by reducing the need for additional cables, splices and handling to connect additional temperature gages. Armoured cables lead to and from each sensor and the protection fittings help prevent damage to series connections in harsh environments. In previous tests [14] on side by side comparisons of FOS and ERS strain gauges on steel , the FOS was more sensitive and more accurate than the ERS gauge when trialled with an accurately calibrated extensometer. It is also claimed that FOS have for greater strain range and 100 times higher fatigue life than other strain sensors although this has not been tested by the Authors. FBGs reflect light centred at a particular wavelength, termed as the Bragg wavelength, which is equal to twice of the product of the effective refractive index of the fibre core and of the grating period. Consequently, a change in temperature and/or in strain can cause a shift in the reflected wavelength through effects such as mechanical and thermal expansion, the photoelastic and the thermo-optic effects. By having two independent fibre gratings exposed to the same surroundings, the strain and temperature can be distinguished by solving the following matrix:

$$\begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} = \frac{1}{D} \begin{bmatrix} K_{\varepsilon 2} & -K_{\varepsilon 1} \\ -K_{T2} & K_{T1} \end{bmatrix} \begin{bmatrix} \Delta \lambda_{B1} \\ \Delta \lambda_{B2} \end{bmatrix}$$

where Kεi is the effective strain coefficient, KTi is the effective temperature coefficient for the fibre gratings, i = 1, 2 referring to gratings 1 and 2, D = KT1Kε 2 − Kε1KT 2 and ΔλBi is the Bragg wavelength shift.

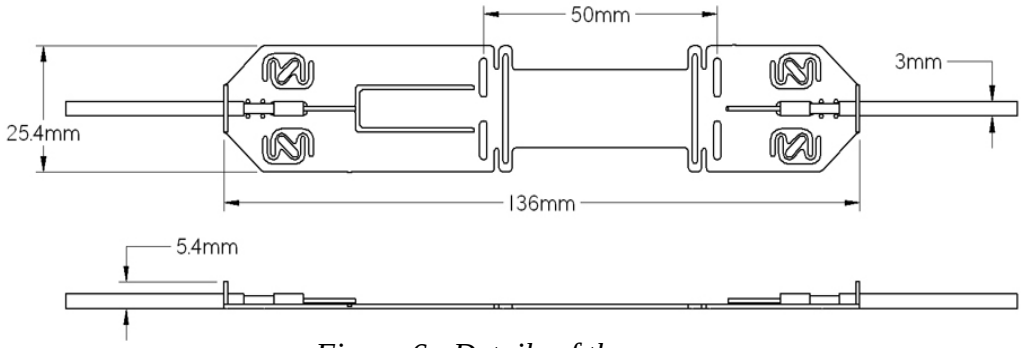

Figure 6 : Details of the sensor

2.2 Set-up of sensors

The main purpose for monitoring the transfer structure was to ensure a safe working environment, assess the load level in the struts and to measure the load distribution between the struts. The position of the sensors is shown in Figure 5 and the fixing of the sensors was carried out in dry condition and the galvanising layer was removed at the location of the sensors to ensure a good bond between the strut and the sensor. A thin layer of marine adhesive was used to attach the sensors and Enlight software translated the change in wavelength from the interrogation unit to changes in strain. The strains were initially recorded every second but this gave far more data than required and the scanning rate was reduced to 1minute intervals. The propping system was installed incrementally as the water level in the cofferdam was reduced. The change in strain was converted into an equivalent change in load assuming a steel elastic modulus of 210kN/mm^2 and a cross-sectional area of 201cm^2 as per designated section in Fig. 5.

2.3 Load levels from sensors

Typical time-load responses are given in figures 7 & 8. The start of monitoring is represented by the zero load reading and all the data reports change in strain/load from this time. Dewatering of the cofferdam first started on 5th of March 2012. Fig 7 shows that, as dewatering occurred, the tide was also changing. This gave an increase in compression force in the struts. On completion of dewatering the struts were continuously monitored while excavation work was carried out but this has been ongoing due to problems with sealing the outer dock walls successfully. Monitoring continued in May and July during further dewatering operations. A maximum load change of 405kN occurred and there were minor fluctuation in the further load levels under tidal changes. The results also indicated that permanent settlement of the pier had taken place and the tidal change now had minimal effect the subsequent change in loads.

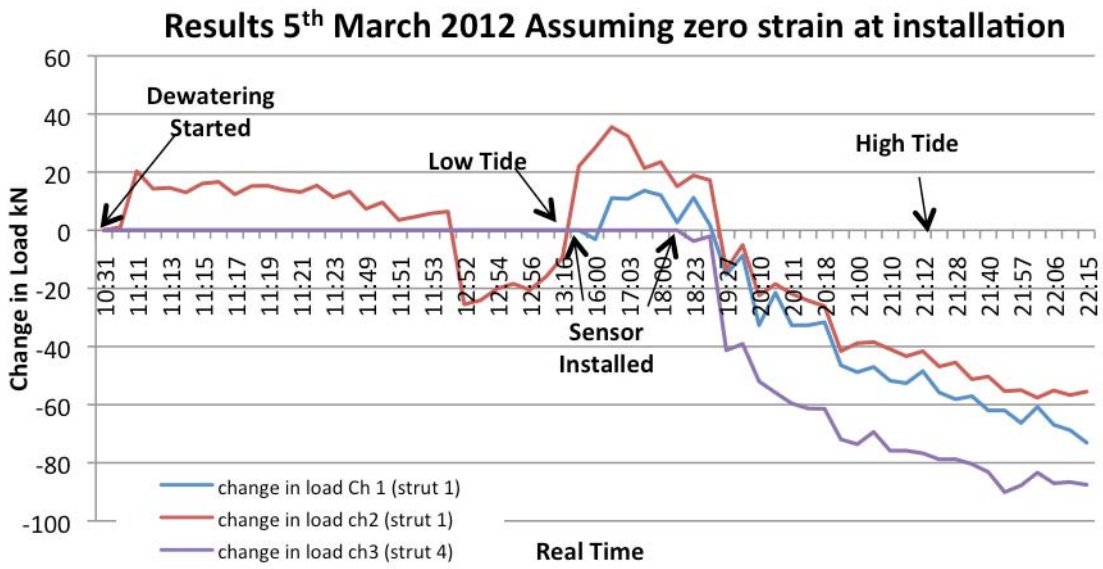

Figure 7: Change in load in the steel strut versus time at start of dewatering

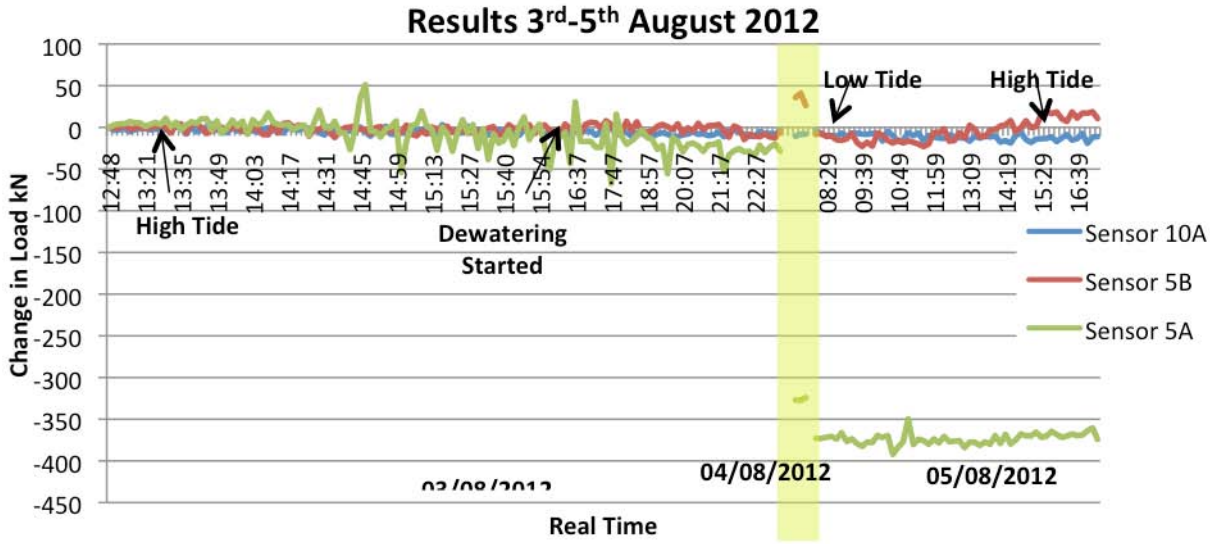

Figure 8: Change in load vs. time August 2012

5. Comparison of monitoring data to design limits of the steel struts

The maximum load on any of the struts to date was 405kN. Using the notation in EC3 and for Grade S355, the following demonstrates the buckling strength of the strut:
For internal compression and the web under pure bending (section is Class 1) the resistance of the section is given by:

$$N_{c,Rd} = \frac{Af_y}{\gamma_{M0}} = 7136\text{kN}$$

Flexural buckling resistance Effective Length of strut both axes: $L_{cr} = L_{cr\,y} = L_{cr\,x} = 0.9$

The column will buckle about the weak (z-z) axis and $\beta_A = 1$ for its class

$$\lambda_z = \frac{L_{crx}}{i_z} \qquad \lambda_1 = 93.9\varepsilon = \qquad \bar{\lambda} = \frac{\lambda_z}{\lambda_1}$$

= 64.5 , 76.4 and = 0.84
using curve c for the buckling curve about the z-z axis and an imperfection factor of 0.49

$$\Phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] = 1.01 \quad \& \quad \chi = \frac{1}{\Phi + \sqrt{\Phi - \bar{\lambda}^2}} = 0.63$$

Hence the buckling resistance: $N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}}$ = 4529kN

The factor of safety (buckling resistance/ max measured applied load/) = 4529/405 = 11.2

5. Conclusions

This paper has given an insight into the safe restoration of one of the iconic structures from shipbuilding industry in Belfast and Thompson's Dry Dock is a dominant feature in the Titanic Quarter and the newly emerged Science park and Innovation Centre. The use of structural monitoring significantly reduced risk in this complex restoration process and in the construction of new temporary and permanent structures. Additionally, the data from the monitoring has served as a check on initial design solutions and in understanding the distribution of high static water pressure and wave loading through the dock wall and new transfer structures. The monitoring confirmed that there was high margin of safety in the design and the load was dispersing safely through the transfer structure. The load levels were lower than had originally been assumed in the initial design calculations probably due to higher dispersal angles at the dock wall and fill.

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