Institution: University of Greenwich

Unit of Assessment: (UoA 12) - Aeronautical, Mechanical, Chemical and Manufacturing Engineering.

Title of case study: Applying computational reliability engineering to the conservation of maritime heritage structures

1. Summary of the impact

The Centre for Numerical Modelling and Process Analysis (CNMPA) was asked in 2004 to apply its expertise in computational reliability engineering, usually used in high technology manufacturing, to help save the Cutty Sark ship and in 2010 to help restore the Medway Queen. This case study details how our computational expertise had impact and in particular:

- substantially aided the conservation and restoration of the historic maritime heritage ships;
- developed a decision support tool for post-restoration maintenance of the vessel;
- demonstrated interdisciplinary collaboration;
- contributed to the local and national heritage tourism industry.

2. Underpinning research

CNMPA uses computational reliability engineering to assess the performance of complex structures. It predicts how multi-component, multi-material systems will behave in myriad situations including variations in temperature, pressure, vibration, humidity, and over time. In 2004 the Cutty Sark Trust turned to the university for help based on our expertise in modelling composite structures such as printed circuit boards [3.4]. The magnificent Victorian tea clipper, moored in Greenwich, had fallen into such poor repair she was at risk of collapse. The ship needed to be dismantled and there was only one chance to get it right. Supported by the trust and the Knowledge Transfer Partnership funding, the centre applied its expertise to aid the trust in saving this maritime treasure for the nation.

The team made a digital model of the Cutty Sark which factored in the materials' aged state and the hull's iron and timber makeup. Existing techniques such as photogrammetry and data from laser scans were used to digitise the ship's structure; acoustic and visual data to obtain data on material loss due to corrosion; and finite element analysis to predict structural behaviour. The finite element model required development of a new shell element formulation to accurately capture the composite structure's behaviour, made of iron and timber planks [3.1]. The main feature of the above approach is the evaluation of the in-plane and bending stiffness of the composite hull structure. This approach was validated against experimental data at the university engineering laboratory, where a small prototype of the ship's hull was built and tested. Using this finite element model the team was able to predict detailed structural behaviour of the ship (eg deformation and stresses) for all the conservation scenarios being suggested by the trust.

The initial phase of the project was to dismantle the ship in order to mend and preserve each component. What CNMPA was able to do, by using the finite element model detailed above, was demonstrate what would happen in 14 different scenarios and give the trust confidence that it was choosing the safest way to dismantle the ship before a single plank had been lifted. CNMPA also applied its computational technologies to the ship's reassembly. We were able to help the trust realise its ambition to raise the Cutty Sark above ground in order to create a museum space, and allow the public to walk beneath the magnificent sculptural hull. In theory our research outputs suggested this would be possible but could it be delivered in practice? Our initial work investigated the option of using a sling to support the ship, but our results showed that this would impose unacceptably high significant stresses on the iron frame [3.5]. Further work produced a better pattern of supports which brought the stresses in the hull down to a very low level. The trust's architect and structural engineer used this information to develop the support structure actually used. Our finite element model investigated the structural integrity of the ship and this new support structure as well as the structural behaviour of the dry dock.

Over 40 internal reports (http://bit.ly/H4JlGh) were generated from our research efforts which helped guide the engineers throughout the conservation programme (2006-2011). Unfortunately in 2007 the ship suffered a major fire which delayed the conservation project by 14 months. We continued to work with the chief engineer and the trust throughout 2008-2009 to assess the structural behaviour of the fire damaged ship, particularly in its planned new support structure.

The team has also developed a novel decision support tool to help maintain the vessel, using Bayesian belief networks with data from a physics model of corrosion, and statistical analysis of sensor data for diagnostics and prognostics of the corroding iron structure [3.3]. Working in collaboration with the University of Portsmouth, it created sensors that gather data on corrosion rates, and combined that with environmental data to demonstrate the use of Bayesian belief networks as part of a prognostics and health management system.

In 2011 CNPMA was approached by Medway Queen Preservation Society to use the experience it gained on modelling the structural behaviour of the Cutty Sark to help restore the Medway Queen (the Heroine of Dunkirk) to its original 1924 design. A novel approach, never used before in such detail to model the restoration of a riveted hull historic ship, used a finite element model for assessing the strength of the rivets and hull plates against a set of defined safety factors [3.2, 3.6]. Our assessment on rivet strength for different sea and passenger loading conditions was validated using tensile tests on samples at the university.

Key staff

Professor Chris Bailey – Director of the Computational Mechanics and Reliability Group within CNMPA and project manager; Dr Stoyan Stoyanov; Dr Yasmine Rosunally – PhD student, now lecturer at University of West London, Dr Pushpa Rajaguru, and Professor Peter Mason – Chief Engineer, Cutty Sark Trust (2004-2009), Visiting Professor, University of Greenwich (2009-present).

3. References to the research (REF1 submitted staff in **bold**, **REF2 submitted output)

3.1 **Stoyanov, S., Mason, P., & Bailey, C. (2010). Smeared shell modelling approach for structural analysis of heritage composite structures – An application to the Cutty Sark conservation. *Computers & Structures*, *88*(11-12), 649–663. http://dx.doi.org/10.1016/j.compstruc.2010.02.005

3.2 Rajaguru, P., Bailey, C., Mason, P., & **Stoyanov, S.** (2013). Buckling Analysis on the Hull of the Paddle Steamer 'Medway Queen'. *Journal for Ships and Offshore Structures*. http://dx.doi.org/10.1080/17445302.2013.849065

3.3 Rosunally, Y. Z., **Stoyanov, S., Bailey, C., Mason, P., Campbell, S., Monger, G., & Campbell, S. (2011). Fusion Approach for Prognostics Framework of Heritage Structure. *Reliability, IEEE Transactions on*, *60*(1), 3–13. http://dx.doi.org/10.1109/TR.2011.2104451

3.4 Bailey, C., Lu, H., & Wheeler, D. (2002). Computational modeling techniques for reliability of electronic components on printed circuit boards. *Applied numerical mathematics*, *40*(1-2), 101–117. http://dx.doi.org/10.1016/S0168-9274(01)00065-4

3.5 Finite Element Predictions for Sling Support for Cutty Sark (2006), internal project report to Cutty Sark Trust. Report available from (http://bit.ly/H4JlGh)

3.6 Structural Assessment of the Hull of the Paddle Steamer “Medway Queen” Final Report (2013)

Further evidence of the quality of the research and the transfer of the knowledge generated in this case study is demonstrated by CNMPA being awarded Times Higher Education Award for Outstanding Research Team (2009) and Best Knowledge Transfer Partnership (KTP) Project for London (2008). The Royal Academy of Engineering also acknowledged the collaboration between the CNMPA and a local organisation as an example of best practice in Knowledge Transfer in a

consultation document to government.

Research grants:

3a C. Bailey. *Cutty Sark KTP Project* (Programme no: 000232) 2004-2008, continuation through funding from Cutty Sark into 2010. Awarded to University of Greenwich, Total funding £150,000.

3b C. Bailey. *Structural Assessment of the Hull of the Paddle Steamer "Medway Queen".* KTP Programme No. 1000672) Awarded to the University of Greenwich, Total funding £51,000.

4. Details of the impact

The direct beneficiaries of the research detailed in section 2 are the Cutty Sark Trust and the Medway Queen Preservation Society. The nation has also benefited from our work, which has helped ensure the people can continue to enjoy these ships, both of which demonstrate our rich maritime heritage.

1) Economic impact:

The results and recommendations arising from CNMPA's research work, detailed in the reports made available to the trust, were implemented throughout 2008-2011. Our work in 2006 led to a change in direction of how the ship would be supported. This saved an estimated £500,000 (the cost if the original option had progressed further) in particular during the period from 2008 onwards, when detailed planning for lifting and supporting the ship was put into practice. Our research helped minimise the risk associated with both disassembly (2006-2007) and reassembly (2008-2011) of the ship. It also reduced the time in planning the procedures for disassembly and reassembly.

The overall cost of saving the Cutty Sark for the nation was £50M of which the Heritage Lottery awarded £25m. Scientific underpinning provided by the university was instrumental in securing Lottery funding, and structural health monitoring work by the university was a condition of the award. An aim was to minimise the amount of new conservation work required for at least 50 years: we developed a decision support tool for post-restoration maintenance of the vessel, ensuring that potential future losses due to structural problems with the ship have been mitigated. Our contribution has also secured local jobs for 20 people who now work on the Cutty Sark. This international icon is helping to boost tourism which plays such an important role in the UK economy, adding £12Bn per year to GDP and supporting over 195,000 jobs.

Ian Diamond, Chair of Research Councils UK, following the team being awarded the Times Higher Education Outstanding Research Team of the year (2009), said of the university's contribution: "*A rare combination of outstanding research and real impact in an area not normally noted for engineering. The application to cultural heritage will have an enormous impact on the UK's long term economy.*" (http://bit.ly/15UsbEg)

The work on the Cutty Sark has exciting implications as our research is generic, and could be used to conserve and maintain other heritage structures. The trust has provided an introduction to a national network of maritime conservation projects, leading to new application in the £5M restoration of the Medway Queen, a survivor of the Dunkirk evacuation. This was a unique ship – fast and light for her day. She was not built to the design rules of the day and there are no modern rules for constructing riveted ships – hence the need for a computational analysis. Our work ensured the contractors' riveting process was safe, and able to withstand the stresses the plating in the ship's hull imposed on the rivets. We also identified safe operating conditions in terms of sea conditions and passenger loading, and the response of the ship's hull to the placement of heavy critical machinery. This helped the restoration programme consultant, a naval architect, ensure the riveted ship would be structurally sound. The Medway Queen Museum is now open in Gillingham,

providing training in maritime conservation skills and employing 24 people.

2) Impact on culture and society:

Today the masts of the Cutty Sark stand tall once again over Greenwich. The Queen reopened the much loved icon in April 2012 and by February 2013 over 320,000 people had visited, half from overseas. The aesthetic pleasure of seeing the ship in that setting and the cultural identity it gives are priceless. No other group has applied this kind of engineering – sophisticated computational and numerical models which are based on detailed physical analysis of failure mechanisms – to the conservation of heritage artefacts. The project has become a popular case study for school, undergraduate and postgraduate students, for instance through annual Royal Institution master classes and IEEE events. Wide media coverage, and prizes awarded to the group, attest to the reputation of the project regionally and nationally. These include the *Times Higher Education Award for Outstanding Research Team* (2009) and *Best Knowledge Transfer Partnership (KTP) Project for London* (2008).

The London Development Agency, following the Knowledge Transfer Awards 2008, said: *"The university's experts are using sophisticated computer models to work out how to dismantle and reassemble the fire-damaged Cutty Sark. They are now using their knowledge to understand how the Cutty Sark's structure will age over the next 100 years. The university is developing the technology to be used on other ships, protecting maritime heritage across the globe."* (*http://bit.ly/17XqIKh*)

The Medway Queen belongs to the national core collection of historic vessels. The aim was for the paddle steamer to gain license to sail once again, ie to meet latest maritime standards (Maritime Coastal Agency) yet be rebuilt using the original 1924 design of a fully riveted structure (http://bit.ly/16kKoNU). Our results ensured that safety requirements were met and the ship sailed from Bristol, where she was rebuilt, home to Gillingham. In fact the amount of detail we provided goes beyond what is usually required for MCA certification and could possibly inform future MCA standards for heritage ships. The Medway Queen Preservation Society aims to exhibit the vessel at the 75th Dunkirk Anniversary in 2015, as well exhibiting at ports around north-west Europe.

5. Sources to corroborate the impact

1) CEO, Cutty Sark Trust, Beneficiary, can provide a statement on the economic and cultural impact our work has had in helping to save the Cutty Sark.
2) Member of Parliament for Greenwich, Beneficiary, can provided a factual statement supporting the impact our work has had on the London Borough of Greenwich through university collaboration with small organisation such as the Cutty Sark Trust.
3) Chief Engineer Cutty Sark Trust (2004-2009), User, can provide s a statement supporting the impact that our work had details of how our work helped inform his engineering decisions and those of the contractors working on the project.
4) Naval Architect & Consultant to the Medway Queen Preservation Society, User, can provide statement to support the impact our work had on the structural assessment of the Medway Queen for different sea and passenger loading conditions.
5) Project Manager, Medway Queen Restoration Project, beneficiary, can provide a statement to support the impact of our work on the Medway Queen.
6) BBC News: http://bbc.in/17CcYW1, demonstrating outreach with the media and informing the public of our work.
7) Knowledge Transfer Partnership Case Study http://bit.ly/H8F6de, details the results from our work and provides a case study for future KTP projects funded by the TSB.
8) Time Higher Education article (http://bit.ly/GWvQrO) Provides details on our project with the Cutty Sark being awarded best KTP partnership for London (2008).