Institution: University of Greenwich

Unit of Assessment: (UoA 11) - Computer Science and Informatics

Title of case study: Computer methods for assessing reliability of complex structures

1. Summary of the impact

The Computational Mechanics and Reliability Group at the University of Greenwich has been developing computational methods for predicting material behaviour and component reliability since the late 1990s. This case study details economic and environmental impacts and impacts on practitioners. In particular it shows how our expertise has:

- substantially aided companies to predict reliability of new electronic systems before physical prototyping providing significant cost savings;
- enabled companies to assess impact of new materials that address environmental legislation;
- provided information to the Cutty Sark Trust in help maintain this national maritime treasure.

2. Underpinning research

The university uses computational methods to assess the performance of engineering structures. It predicts how multi-component, multi-material systems will behave in myriad situations including variations in temperature, pressure, vibration, humidity, and over time. A central theme of the work is the development of methodologies for acquiring data, and predicting material behaviour and reliability of complex engineering structures – from heritage ships to miniaturised electronic components.

a) Multi-physics modelling and optimisation

Research began in the early 90s when we developed multi-physics tool PHYSICA which uses finite volume and finite element techniques to solve the governing equations of fluid flow, heat transfer, and stress in a coupled manner on high performance computers [3.1]. We have coupled these predictions with numerical optimisation tools to provide a framework that is capable of performing design optimisation procedures in an entirely automated and systematic manner [3.2]. Supported by numerous EPSRC projects [3a, 3b] this framework was used to predict the reliability of miniaturised electronic components. To use these tools effectively we required data from physical experiments and the input of design constraints such as environmental operating conditions. With these inputs, this framework was used to optimise the design of underfill materials and solder joints in packaged electronic components that addressed EU legislation such as the Reduction of Hazardous Substances Directive. Outputs from our work were used by our industrial partners Henkel, Celestica, MicroEmmisive Displays, DEK Printing Machines to provide information that was used to optimise their manufacturing processes.

Funded by the US Government [3c] in collaboration with Selex-Electronic Systems, Rolls Royce, General Dynamics, and Micross Semiconductors, we have extended the above approach so that our computational analysis is used within the qualification process for assessing the performance of a robotic controlled refinishing process for semiconductor packages that are to be used in high reliability applications. To ensure that the thermal modelling techniques have accurate input data we have integrated data obtained from material characterisation (eg Scanning Electron Microscopy, Scanning Acoustic Microscopy), and internal semiconductor package geometric characterisation (eg computer tomography) within the thermal modelling computer analysis software. For example data from computer tomography (eg .stl files) is used to develop the finite element models of the semiconductor package and data from scanning acoustic microscopy to assess any damage in the package. The results from the thermo-mechanical modelling analysis has been used to investigate different operating conditions of the robotic controlled refinishing process and hence optimise this process in terms of the temperatures that the semiconductor device is exposed to during manufacture [3.3].

b) Surrogate modelling

Undertaking extensive finite element analysis of semiconductor packages within a design space that has multi-dimensions in terms of design variables, and whose values will have manufacturing variability, is far too time consuming even for the most powerful computers. To address this we have used optimisation and statistical techniques to develop surrogate models whose predictive accuracy is the equivalent of a detailed finite element model in assessing the reliability of these packages. This work was originally supported under a Department of Trade and Industry project [3e] in collaboration with Dynex Semiconductors and SEMELAB and extended under the EU project PEMREL [3f]. Here we used design of simulation techniques to develop fast surrogate models that can be used to predict stress in the semiconductor packages when subjected to thermal or vibration loadings [3.4]. This led on to the development of the PowerLife software tool which embeds these surrogate models for power electronic package reliability assessment. This tool is now used within both companies to optimise designs of power modules before physical prototyping.

c) Prognostics and health monitoring

The ability to use surrogate models to predict semiconductor package material behaviour has led on to the development of prognostics and health management tools to monitor the remaining useful life of semiconductor packages when they are used in the field: in particular for high power Light Emitting Diodes (LED) where we used computational learning algorithms to monitor the degradation of light emitted by the diode by monitoring changes in electrical current and voltage of the semiconductor [3.5]. Our expertise in this area has also been used to monitor the degradation of aged heritage structures (eg the iron frame of the Cutty Sark clipper ship) where we have demonstrated that data from sensors monitoring temperature changes, humidity and footfall can be used within a Bayesian Network to assess degradation of the iron frame over time [3.6]. This work was supported by the Cutty Sark Trust in parallel with a Knowledge Transfer Project [3g] that investigated the structural behaviour of the ship during the recent conservation programme.

Key staff: Professor Chris Bailey – Director of the Computational Mechanics and Reliability Group and project manager; Dr Stoyan Stoyanov (Reader), Dr Yasmine Rosunally (now at University of West London), Dr Xiangdong Xue (now at University of Sheffield).

3. References to the research (REF1 submittd staff in **bold**, **REF2 Output)

3.1 Bailey, C., Chow, P., Cross, M., Fryer, Y., & Pericleous, K. (1996). Multiphysics Modelling of the Metals Casting Process. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, *452*(1946), 459–486. http://dx.doi.org/10.1098/rspa.1996.0024

3.2 **Stoyanov, S.**, Bailey, C., & Cross, M. (2002). Optimisation modelling for flip-chip solder joint reliability. *Soldering & Surface Mount Technology*, *14*(1), 49–58. http://dx.doi.org/10.1108/09540910210416477

3.3 **Stoyanov, S.**, Best, C., Yin, C., Alam, M. O., Bailey, C., & Tollafield, P. (2012). Experimental and modelling study on the effects of refinishing lead-free microelectronic components (pp. 1–6). Presented at the Electronic System-Integration Technology Conference (ESTC), 2012 4th, IEEE. Amsterdam, Neitherlands. http://dx.doi.org/10.1109/ESTC.2012

3.4 Xue, X., Bailey, C., Lu, H., & **Stoyanov, S.** (2011). Integration of analytical techniques in stochastic optimization of microsystem reliability. *Microelectronics Reliability*, *51*(5), 936–945. http://dx.doi.org/10.1016/j.microrel.2011.01.008

3.5 Sutharssan, T., **Stoyanov, S., Bailey, C., & Rosunally, Y. (2012). Prognostics and Health

Monitoring of High Power LED. *Micromachines*, *3*(1), 78-100. http://dx.doi.org/10.3390/mi3010078

3.6 Rosunally, Y., **Stoyanov, S.,** Bailey, C., Mason, P., Campbell, S., Monger, G., & Bell, I. (2010). Bayesian Networks for Predicting remaining Life. *International Journal of Performability Engineering*, *6*(5), 499-512.

Research/consultancy grants:

3a EPSRC (GR/N14095), 2000-2002, £110,000 - *Lead-Free Soldering for Flip-Chip Assembly Applications*

3b EPSRC (GR/R09190 and GR/R09206/02), 2001-2003, £243,463 - *Microsystems Assembly Technology for the 21St Century – MAT21*

3c US Government (H94003-04-D-003-0056), 2011-2014, US$320,000

3d DTi (TP/3/DSM/6/I/16796), 2006-2009, £230,962 - *Modelling Power Modules (MPM)*

3e EU Clean Skies (Grant No. 271788), 2010-2013, 200,000 euros - PEMREL

3f 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.

4. Details of the impact

Economic impact

The value of the electronics manufacturing industry worldwide is ~US$2tn; Europe accounts for ~20% of this. Advances in electronics components and systems technologies underpin much larger markets which include industrial sectors, eg aerospace, automotive, energy generation, medical devices etc, and service sectors, eg internet, games, broadcasting, telecoms etc, which account for approximately 10% of world GDP.

Our multi-physics[(1)] and optimisation work[(2)], in collaboration with Henkel, DEK Printing machines, and Celestica, has provided a route to predict the reliability of sub-100um pitch interconnections using lead-free solder pastes. Our work in optimising the refinishing process of electronic components for use in high reliability aerospace applications[(3)] has been funded by the US Department of Defense and industry, and has developed a methodology to reduce dramatically the amount of physical testing required to prove integrity, where normally such testing can cost upwards of £100,000 per component.

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[(6)] for post-restoration maintenance of the vessel, ensuring that potential future losses due to structural problems with the ship have been mitigated. Our overall 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.

Environmental impact

European legislation such as the Reduction of Hazardous Substances (RoHS), and Waste Electrical and Electronic Equipment directives, have posed significant challenges for the electronics industry in finding replacements to a number of materials used in electronics manufacturing – including lead-based solders. Our work in assessing the reliability of electronic components using material replacements such as Tin-Silver-Copper solders[(2-4)] has helped our industry partners meet these challenges as well as avoid the placement of harmful materials such as lead in landfill. Although RoHS only applied to certain sectors (eg high reliability sectors have an opt-out) the use of commercial lead-free components in high reliability systems means that that most sectors have had to abide with the RoHS legislation. Our work on power electronics modules[4] and the use of our tool – PowerLife – by industrial partners is providing a route for the adoption of power electronics modules in a wide range of applications including aerospace, rail and automotive. For example our work on glob-top materials clearly identified this as a process to increase the reliability of wirebond interconnects in harsh environments. The adoption of power electronics has the potential for energy savings of $400Bn annually and the UK is well placed to benefit from innovations in this area.

Impact on practitioners

Our work has resulted in design rules for a number of companies who are using these to ensure that quality and reliability requirements of their components are met. Examples include Selex Electronic Systems, who are using our modelling technologies as part of their qualification process for avionics electronics. In addition to this our expertise in computational intelligence and prognostics[5,6] is contributing to the new IEEE Standard P1856 (http://bit.ly/1a2eZy0) – Prognostics and Health Management of Electronic Systems. Our modelling expertise has also contributed to the 2013 International Electronics Manufacturing Initiative Roadmap (http://bit.ly/1ea0Hjk). We work closely with the National Microelectronics Institute and the IEEE (where Professor Bailey is UK&RI Chapter Chair for the IEEE Components, Packaging, and Manufacturing Technology Society, and Reliability Society) in disseminating our research outputs to practitioners.

5. Sources to corroborate the impact

1. Director of Product Development, Henkel Technologies (UK), Beneficiary, can provide a statement on the impact our work has had on new solder and adhesive materials development
2. CTO, Selex-Electronic Systems, Beneficiary, can provide a statement on the impact of our work for predicting the reliability of avionic electronic systems
3. R&D Manager, Dynex Semiconductors Limited, User, can provide a statement on the impact of our work for predicting the reliability of power electronics modules
4. Chief Engineer Cutty Sark Trust (2004-2009), User, can provide 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.
5. Engineering Director, Micross Semiconductor Limited, Beneficiary, Can provide a statement on how our work on the robotic refinishing process has helped optimise the process.
6. IEEE Standard P1856 (http://bit.ly/1a2eZy0) – Standard Framework for Prognostics and Health Management of Electronic Systems, Chair is Professor Michael Pecht (pecht@calce.umd.edu), University of Maryland. University of Greenwich based on its research in reliability of electronics systems is a member of the working group.
7. BBC News: http://bbc.in/17CcYW1, demonstrating outreach with the media and informing the public of our work for the heritage sector.