Institution: University of Bristol

Unit of Assessment: 15 - General Engineering

Title of case study: Veqter - exploiting residual stress measurement technique to provide unique structural integrity assessment service

1. Summary of the impact (indicative maximum 100 words)

Residual stresses are the stresses locked into a component during manufacture. It is essential that the magnitudes of these residual stress fields are known as they may combine deleteriously with applied loads. This can lead to premature failure, of a component or structure, at loads the designer would otherwise view as safe. Researchers at Bristol have developed a residual stress measurement technique called *deep-hole drilling,* which allows measurements of residual stresses both near the surface and throughout the thickness of the specimen, even for very large components which other methods are unable to measure. Veqter Ltd was created in 2004 as a University spin-out company to provide deep-hole drilling residual stress measurements for industry. The company has grown *[text removed for publication]*. Primarily, Veqter is a service company, undertaking laboratory and *on-site* residual stress measurements on safety-critical components using hardware and analysis algorithms developed at the University. It is the only company worldwide that offers this facility and its customer base includes EDF Energy, the Japan Nuclear Energy Safety Organisation, the US Nuclear Regulatory Commission and Airbus. Veqter's measurements allow these companies to better understand the structural integrity of safety-critical plant.

2. Underpinning research (indicative maximum 500 words)

The presence of residual stresses can cause components or structures to fail at lower load levels than anticipated. Residual stress measurements are therefore needed for safety critical plant, such as those in the nuclear and aerospace sectors. In thick-sectioned components (perhaps >100mm thick), however, there was a paucity of reliable measurement techniques. To address this problem, Bristol's ***Solid Mechanics*** Group has developed the deep-hole drilling technique. This is a semi-destructive technique requiring only a minimal amount of material removal from the component being examined. Note, in contrast to destructive techniques, the overall structural integrity of the component is left intact allowing further testing or repair and reuse.

Smith (UoB since 1988) started research on the measurement technique and its basic implementation in the late 1990s. This original technique has been progressively advanced and refined through the 2000s by Smith, Truman (UoB since 2000) and Pavier (UoB since 1989). Key underpinning research, conducted by the University's Group and adopted by its spin-out company Veqter Ltd for commercial exploitation include the following:

- George (UoB RA 1995-2001) and Smith demonstrated the basic proof-of-concept measurement technique on welds joining industrial components [1].
  Welding, the principal joining process between metallic components, introduces highly tensile residual stresses due to the molten metal cooling and contracting. This research assesses the accuracy of residual stress measurements on a selection of components originating from the nuclear industry, which leads the way in assessing safety critical components. Whilst a handful of residual stress measurement techniques already exist, such as neutron diffraction, slitting and ring-core they are all limited to thin sections. This paper demonstrated that deep-hole drilling is capable of providing reliable through-thickness measurements in large metallic components.

- Kingston (UoB RA 1998-2004 and Veqter since 2004), Smith and Truman developed the technique to measure geometrically complex industrial components [2,3].
  The original deep-hole drilling analysis utilised an underlying elasticity solution for the stresses around a hole in an infinite plate subjected to far field loading and so was only applicable to

simply shaped components. This research removed these restrictions by advancing the theoretical and experimental procedures. These advances were demonstrated by taking accurate experimental residual stress measurements for a series of complex shaped industrial components, such as nozzle-pipe interactions and inclined penetration welds.

- Nakhodchi (UoB RA 2005-11), Smith, Truman and Pavier extended the technique to measure residual stresses in non-metallic materials, e.g. composites, graphite and glasses [4].
  The underpinning solution used for data analysis in deep-hole drilling had made the assumption that the component being measured was fabricated from isotropic materials. In order to extend the method to provide measurement results in anisotropic materials, such as composites, major extensions to the data analysis were required. This work provided those extensions and successfully applied deep-hole drilling to a composite component originating from the aerospace industry.

- Mahmoudi (UoB RA 2000-2008), Pavier, Truman and Smith developed a method to measure samples containing near-yield magnitude residual stresses accurately [5,6].
  With improvements in the modelling of residual stresses and the demand to measure ever more complex components (such as dissimilar metal welds), it was desirable to move away from employing the underpinning elasticity assumption. If possible, this would facilitate the measurement of specimens where residual stress magnitudes were high relative to the yield stress of the material and triaxial in nature (with significant residual stress components in all three coordinate axis directions). This research addressed this problem and provided a formulation and methodology to apply the deep-hole drilling technique irrespective of residual stress magnitude and triaxiality.

3. References to the research (indicative maximum of six references)

[1] *D.J. Smith, P.J. Bouchard and D. George, 2000. *Measurement and prediction of residual stresses in thick section steel welds*. Journal of Strain Analysis for Engineering Design, 35(4), 483-497, dx.doi.org/10.1243/0309324001514422.

[2] D. Stefanescu, C.E. Truman and D.J. Smith, 2004. *An integrated approach for measuring near and sub-surface residual stress in engineering components*. Journal of Strain Analysis for Engineering Design, 39(5), 483-497, dx.doi.org/10.1243/0309324041896524.

[3] S. Hossain, C.E. Truman, D.J. Smith and P.J. Bouchard, 2006. *Measurement of residual stresses in a type 316H stainless steel offset repair in a pipe girth weld*. ASME Journal of Pressure Vessel Technology, 128(3), 420-426, dx.doi.org/10.1115/1.2218346.

[4] M.G. Bateman, O.H. Miller, T.J. Palmer, C.E.P. Breen, E.J. Kingston, D.J. Smith and M.J. Pavier, 2005. *Measurement of residual stress in thick section composite laminates using the deep-hole method*. International Journal of Mechanical Sciences, 47(11), 1718-1739, dx.doi.org/10.1016/j.ijmecsci.2005.06.011.

[5] *A. Mahmoudi, S. Hossain, C.E. Truman, D.J. Smith and M.J. Pavier, 2009. *A new procedure to measure near yield residual stresses using the deep hole drilling technique*. Experimental Mechanics, 49(4), 595-604, dx.doi.org/10.1007/s11340-008-9164-y (listed in REF2).

[6] *A.H. Mahmoudi, C.E. Truman, D.J. Smith and M.J. Pavier, 2011. *The effect of plasticity on the ability of the deep hole drilling technique to measure axisymmetric residual stress*. International Journal of Mechanical Sciences, 53(11), p78-988, dx.doi.org/10.1016/j.ijmecsci.2011.08.002 (listed in REF2).

* References that best indicate the quality of the underpinning research.

4. Details of the impact (indicative maximum 750 words)

Undertaking fully through-thickness residual stress measurements in thick-sectioned industrial components is expensive, whichever technique is employed. Neutron diffraction measurements are often viewed as the nearest measurement alternative to deep-hole drilling, as they are able to measure sub-surface residual stresses in crystalline materials. However, neutron diffraction is only able to make measurements to a depth of approximately 30mm in steel and commercial costs of neutron beam time are in the region of £15-20k per day. Bristol's deep-hole drilling technique, in contrast, can be used to take residual stress measurements on much thicker components. To date, the deepest measurement – 750mm – was taken on a steel turbine for Siemens [a]. Costs are primarily determined by the time to undertake the measurement. As an example, an on-site measurement on a large nuclear component may take a week to perform.

Using the University's deep-hole drilling technique, and its associated data analysis methods, Veqter Ltd provide commercial residual stress measurements for use in structural integrity assessments. The company undertakes the measurement service on structural-level samples sent to the laboratory or, for larger components, conducts the service in-situ at the plant. The company was formed in 2004 by Kingston (UoB 1998-2004) when it became apparent that the quick turnaround of measurements demanded by industry, coupled with confidentiality requirements, necessitated the need for an independent, commercial spin-out company. Smith and Truman remain non-executive directors on the Board of Veqter. Since the company was formed, the key impact indicators are [b]:

- The growth from *[text removed for publication]* employees (2004-2011).
- The growth in annual turnover *[text removed for publication]*.
- The steady increase in the client base from across the world, including Japan, America and France.
- Veqter appointing a dedicated Japanese agent, IIC, in 2008 to extend operations in this country.

In addition to the direct economic impact for Veqter, its unique measurement service, often applied to safety-critical hardware, has significant impact for its clients. The through-thickness residual stress profile measurements allow the client to undertake detailed fitness for service assessments or to validate numerical simulations. Examples relating to the design and repair of components in the nuclear industry include:

- In 2010-11, deep-hole drilling measurement results were used in a series of plant life extensions for *EDF Energy* (formerly British Energy Generation Ltd) to help extend the life of the current fleet of advanced gas-cooled nuclear reactors.
  As an example, full structural weld overlays have been used extensively to repair, or to mitigate against, primary water stress corrosion cracking at dissimilar metal welds in pressurized nozzles. To support an approved weld overlay design and safety submission, British Energy commissioned Veqter to perform tests on pressurized water reactor nozzles. Specifically, a detailed assessment of the effects of a weld overlay on the through-wall residual stress distribution in these nozzles was conducted using deep-hole drilling. This study allowed EDF to determine the most appropriate form of weld overlay to apply to their plant to maximize confidence in the structural integrity case [b,c].

- The *US Nuclear Regulatory Commission* are employing deep-hole drilling to measure and validate through-wall weld residual stresses that develop at the J-groove welds in nuclear control rod mechanisms [d].
  The Commission and the Electric Power Research Institute worked cooperatively to validate residual stress predictions at welds between primary cooling loop components. The residual stress distribution for the prototype component was predicted numerically using different techniques. Veqter provided experimental measurements for comparison. The Commission noted, in 2011, that due to the thickness of the components "*The only non-destructive or semi-destructive technique capable of obtaining full through the wall residual stress … is the VEQTER Ltd proprietary Deep Hole Drilling technique*" [d]. The results of this study showed that, on average, analysts can develop welding residual stress predictions that are a reasonable estimate for actual configurations, as quantified by Veqter's measurements. However, the scatter in predicted results from analyst to analyst could be quite large. These results allowed the Commission to understand the limitations of numerical weld simulation models and hence place an appropriate error on numerical results [b,e].

- The *Japan Nuclear Energy Safety Organisation* has employed deep-hole drilling in a series of key national nuclear safety projects [b].
  As an example, in recent years, the occurrence of stress corrosion cracking in Alloy 600 weld

regions of pressurized water reactor plants has increased. In order to evaluate crack propagation mechanisms, it was necessary to estimate the stress distribution, including residual stress and operational stress, across the wall thickness in the region of the weld. In a national project, for the purpose of establishing the optimum residual stress evaluation method, a test model was produced. The stress distribution, resulting from fabrication processes, was measured by Veqter using the deep-hole drilling technique. The results showed that the stress distribution, in the thickness direction at the centre of the weld line, hardly varied during a hydrostatic test. This insight allowed the Safety Organisation to validate the numerical safety simulations performed by plant fabricators Toshiba, Hitachi and MHI [b].

- *AREVA plc* have placed high value on the use of Veqter's deep-hole drilling measurements in the development of narrow gap TIG welding.
  For new nuclear builds, AREVA has developed an advanced narrow gap welding technique for junctions between heavy section steel components and stainless steel piping. The company used finite element simulations to predict the residual stress field of a 29" multipass narrow gap weld. These numerical results were compared to Veqter's measurements obtained by the deep-hole drilling technique. This comparison provided data that allowed AREVA to gain a better insight into the error levels associated with numerical weld simulation modeling [b,f].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[a] Diesel & Gas Worldwide article *Measuring the Stress in Turbines*, April 2012.
[b] Managing Director, Veqter.
[c] Former Principal engineer, EDF Energy.
[d] U.S. Nuclear Regulatory Commission: *Weld Residual Stress Measurements for Reactor Vessel Bottom Mounted instrument and Control Rod Drive Mechanism Nozzles* purchase order announcement, August 2011.
[e] Chief - Component Integrity Branch, U.S. Nuclear Regulatory Commission.
[f] AREVA Expert in Mechanics & Materials, AREVA.