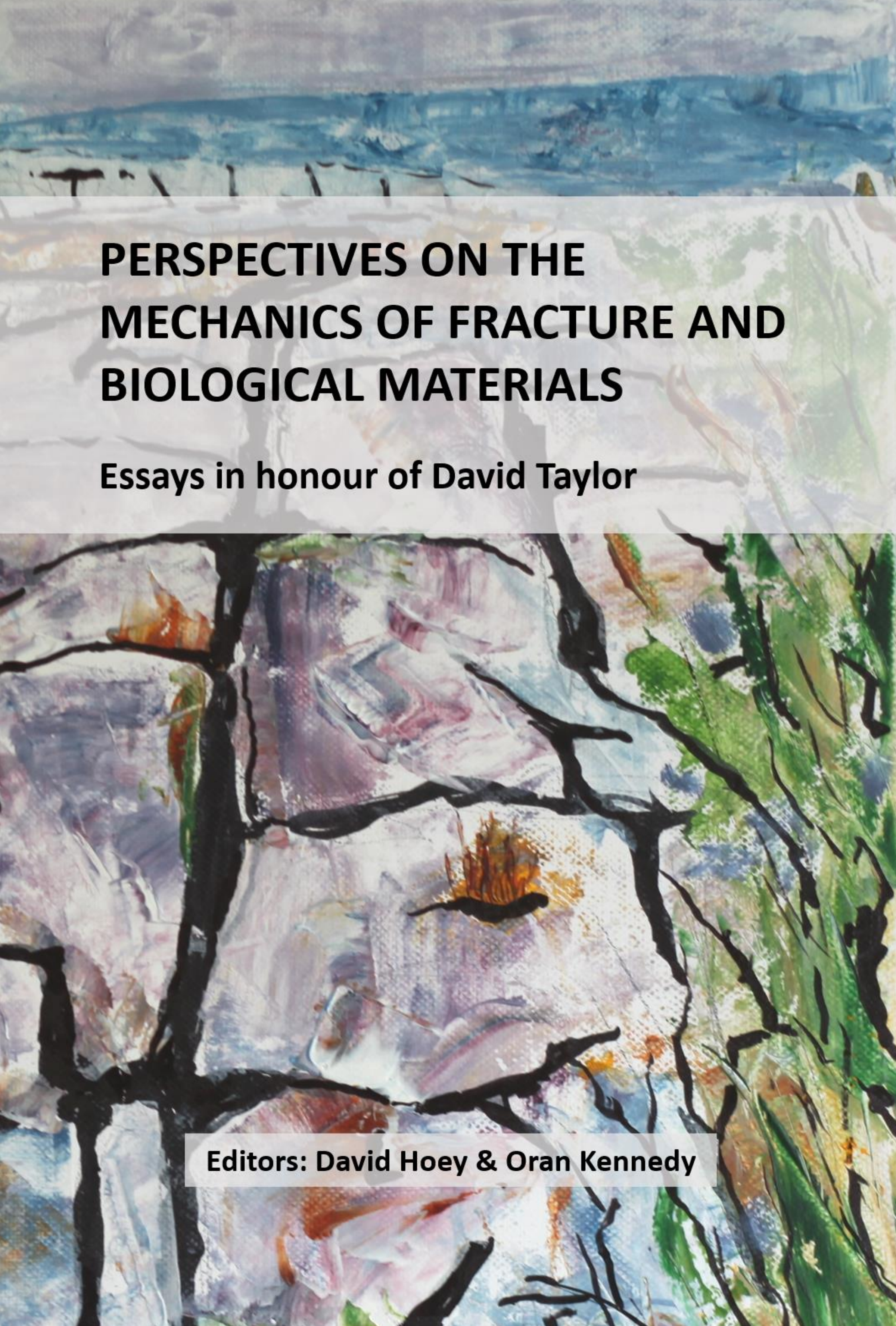

PERSPECTIVES ON THE MECHANICS OF FRACTURE AND BIOLOGICAL MATERIALS

Essays in honour of David Taylor

Editors: David Hoey & Oran Kennedy

Front Cover:
Fractured Landscapes,
by David Taylor

This painting was part of a series called "*Fractured Landscapes*" exhibited by Prof. David Taylor on the day of his Festschrift in Trinity College Dublin on the 1st of September 2022. Made with acrylic paint and ink on canvas it shows the landscape of the Burren in County Clare, Ireland.

Perspectives on the Mechanics of Fracture and Biological Materials

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Essays in honour of David Taylor

David A. Hoey & Oran D. Kennedy

Editors

Published by
Department of Mechanical, Manufacturing, & Biomedical Engineering, Trinity College Dublin, Dublin 2, Ireland

&

Department of Anatomy & Regenerative Medicine, Royal College of Surgeons in Ireland, Dublin 2, Ireland.

ISBN 978-1-4716-1942-7

Published with the financial assistance of
Trinity College Dublin &
the Royal College of Surgeons in Ireland

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FOREWORD

The planning of David Taylor’s Festschrift celebration, like many things, was subject to the vagaries of Covid-19 interruptions. The outcome is that the event and the Festschrift publication are all about a year late. In that context I'm particularly grateful to David Hoey and Oran Kennedy who maintained a steady eye on the outcome, which was to have a face-to-face celebration (no Zoom event would do) in honour of David Taylor's working life, accompanied by a series of essays by some of the people who have worked with David over the years.

David worked with and inspired many people and it is therefore not a surprise that many people were so willing to contribute essays to this volume. The result is that the Festschrift is a great mix of essays from different walks of David's professional life. One category of contributions is from Trinity College colleagues (Patrick Prendergast, Peter O'Reilly, Conor Buckley, Daniel Kelly, Caitriona Lally, David Hoey, Ciaran Simms) addressing different aspects of David's life in Trinity, from experimental testing to introducing biomechanics research to TCD, and also his teaching record. Another category of contributions is from some of his former PhD students and research team (Fergal O’Brien, Jan-Henning Dirks, David Hoey, Oran Kennedy), addressing different aspects in failure mechanics. Those two categories would probably suffice for a “normal Festschrift”, but as David Taylor has had such a wide-ranging professional career, there are also contributions from forensic practitioners (Sarah Reid and Donal Terry), as well as from Markus Buehler as a tribute to David's founding of the Journal of the Mechanical Behaviour of Biomedical Materials and his working connections in Italy (Luca Susmel). Clive Lee and Brendan McCormack provide unique reflections on David's early biomechanics research. Finally, on a topic I believe to be close to David's heart, there is a contribution from Olivia Hassett on the interface between art and science.

I thank all the contributors for their essays, and I thank David for allowing us to have this celebration of his work which has been a great part of life in TCD Engineering for over four decades.

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PREFACE

It has been an immense pleasure for us to draw together and edit this Festschrift in honour of our friend and colleague Prof. David Taylor. These essays have been a wonderful experience to review, and the exercise has served as a powerful reminder of the seemly endless number of research areas in which David has explored, and to which he has made significant contributions.

The unifying theme among of all these areas is, of course, fracture. In the Oxford English dictionary, the definition of this word includes descriptions like *'the breaking or cracking of a hard object or material'* and *'to split something into several parts so that it can no longer function'.* The former definition certainly reflects what has fuelled David's imagination, creativity, and productivity throughout his career. As described in these pages, David spent many years examining this phenomenon in a diverse array of materials including metals, bones, eggshells, and insect cuticles. His reasons for doing so were equally diverse, some were for the purposes of forensic investigations, others were part of a wider collaborative biomedical research program, and others still were simply because he thought it might be interesting and/or fun. The latter definition of the word, if applied to David's wider role in the academic community, is not quite so applicable, and in fact is a precisely opposite description of his role and standing among students and colleagues. Rather than splitting or separating things so that they cannot function, David has been (and will hopefully continue to be!) a great unifier, collaborator, and builder of things that are greater than the sum of their parts. From his activities at local, national, or international level, David has always brought calm, positive, and insightful contributions. As examples of these we could cite the growth of the Department of Mechanical, Manufacturing, and Biomedical Engineering in TCD, the expansion of Bioengineering in Ireland as a national organisation, and his leadership of the Journal of the Mechanical Behaviour of Biomedical Materials as a leading international journal, respectively.

The editors are extremely grateful to the Department of Anatomy and Regenerative Medicine in the Royal College of Surgeons in Ireland and to the Department of Mechanical, Manufacturing, and Biomedical Engineering in Trinity College Dublin for financial assistance with the publication of this Festschrift. To all the authors and speakers who gave of their time, we thank you for your efforts. We appreciate also the assistance of all the administrative and technical staff, particularly Judy Lee and Mick Reilly, in the preparation for the event. Finally, a special mention to Ciaran Simms who has been an excellent sounding board and support in the organisation of this joyous occasion.

Last but not least, we would like to thank David himself for being such a wonderful teacher, mentor, colleague, and friend to both of us over the years. We hope he will enjoy reading these works and we wish him as much pleasure and enjoyment in his retirement, as he has given to all of us (and so many others) during his career.

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DAVID TAYLOR – FACTS & REFLECTIONS

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ABSTRACT

This biographical sketch describes the life and career of David Taylor. It spans the period from his birth in England in March 1956 until his retirement *Festschrift* in Trinity College Dublin, in September 2022. His career has been marked by a distinguished body of work, glittering prizes, and institutions and individuals that will forever be in his debt.

1. EARLY LIFE

David Taylor was born in Doncaster, South Yorkshire, on 21st March 1956, the only son of Norman and Marjorie Taylor. Norman's father had been a coal miner and Norman left school at 14 to go down the pit. However, he later went to night school and qualified as a mechanical engineer, working in a brick making company and as a teacher in a technical college. Marjorie was a typist, but as was usual at the time, gave up her job when she married. David did well in his Eleven Plus exam and attended the Percy Jackson Grammar School which, during his time there, merged with the secondary modern school and was named Adwick School, which had about 2000 pupils (Fig. 1).

While David was not good at football, he did help others with their homework, and did not suffer from bullying. In the 6th Form, he took up photography and availed of the school darkroom. The school was streamed, and David benefitted from excellent teaching, most notably in geography from Mr Oliver, who introduced him to the scientific method. David was at the top of the A stream, but he was still surprised when the school put him forward for Cambridge. He attended an interview at Queens' College and was offered a place if he got 3 As in his A Level Maths, Physics and Chemistry. As it transpired, he got 2 As and 2 Bs (the fourth subject was General Studies), but Queens' took him anyway and he was awarded a County Scholarship in 1974 (Fig. 1). David enjoyed his time at Adwick

School and will be sad to learn that it has since been demolished and replaced by Outwood Academy.

Figure 1. Adwick School and Honours Board.

2. CAMBRIDGE

Along with his scholarship, these were the days of student grants, so David was able to go up to Queens' College, Cambridge. The apostrophe in the name is important as two queens are involved, the college having been founded in 1448 by Margaret of Anjou, and refounded in 1465 by the rival queen Elizabeth Woodville. That said, the full name is 'The Queen's College of St Margaret and St Bernard, commonly called Queens' College, in the University of Cambridge'. Aside from David, its alumni include Erasmus, actor Stephen Fry and journalist Emily Maitlis. The college spans the River Cam, and the two halves are connected by the Mathematical Bridge, built in 1749. David had rooms in the Fisher Building and so would have regularly crossed this excellent example of tangent and radial trussing. The tangential members are highlighted in Fig. 2.

Figure 2. Mathematical Bridge over the Cam.

David studied Natural Sciences for three years. In Year 1, he took Maths, Physics, Crystalline State (materials) and Introduction to Biology. He had come from being best in his class at school and able to cover everything, to college where he was covering more ground and mixing with equally bright students, some of whom were much more confident. He thought that he was way behind his peers and was convinced that he had failed his final exams, so he said goodbye to his classmates. Fortunately, he was mistaken, got a II.I and passage to Year 2 – Maths, Physics and Metallurgy, and Final Year, when he specialised in Metallurgy. He joined the College Players and, starting small, gained bigger parts in plays, principally Shakespeare, culminating in his role as Feste, a Clown and servant to Olivia, in *Twelfth Night*. Feste is 'a wise fool among the foolish wise, merry yet shrewd'! David represented Cambridge at tiddlywinks, a game which combines manual dexterity, strategic thought and tactics, and was awarded a quarter blue for defeating Oxford (Fig. 3).

Figure 3. Tiddlywinks Team, 1977-78, at the Fitzwilliam Museum.

David spent the holidays working in a limestone quarry, in a wire rope factory, and hitching and interrailing around Europe. He undertook his final year project with John Knott and graduated in 1977 (Fig. 4).

Figure 4. The Taylor family at David's graduation, 1977.

David then undertook a PhD in fracture mechanics with Knott. Awarded in 1981, his PhD thesis was entitled 'Fatigue crack propagation in nickel, aluminium, bronze castings', and these are important as they are used to make ships' propellers. Around this time, he began directing plays: an early success was JM Synge's *The Playboy of the Western World* which featured (as The Widow Quinn) Joanna Scanlon, who recently won a BAFTA for best actress. The acting, winking and research were all going so well that he stayed on for a postdoc in Cambridge (Fig. 5).

Figure 5. Cambridge University Department of Metallurgy – David is in the back row, wearing a hat.

3. DUBLIN CALLING

Meanwhile in Dublin, David Taplin had been appointed Head of the recently established Department of Mechanical and Manufacturing Engineering in Trinity (Fig. 6). Built in the 1880s as the School of Pathology, it was renamed the Parsons Building in 1981, though its external appearance was little altered.

Figure 6. School of Pathology, 1888; Parsons Building, 1981.

Taplin contacted John Knott in Cambridge to see if he had any promising postdocs. He did, and so David Taylor was invited to an interview for a lecturer post in Trinity in January 1983. David had never been to Ireland and knew little of the country, bar being a Chieftains fan, while his knowledge of Trinity was based on the writings of J.P. Donleavy. He arrived in Dun Laoghaire by boat from Holyhead and was pleasantly surprised by both what he saw and to find the natives - David Taplin, Garret Scaife, John Fitzpatrick, John Monaghan, Andrew Torrance, Garry Lyons, Jim McGovern, Bernard Corbally, David Rees *et al*. – friendly. As a materials scientist, David found himself doing much of the teaching previously allocated to his Head of Department. *Plus ça change*! The Accommodation Office in Trinity put him in touch with a theology lecturer who was looking for someone to share a house, so home was in Ballinteer for the first few years.

4. SOCIAL & PERSONAL

At 26, David was not much older that his students and was made welcome in DU Players, where his contemporaries were the *Rough Magic Theatre Company* in embryo – Director Lynne Parker and actors Arthur Riordan, Anne Enright, Martin Murphy and Pauline McLynn. David starred as King John in the eponymous, but rarely-performed, Shakespearian play, and directed *Galileo* by Bertolt Brecht. Summer companies were formed, as had been the case in Cambridge, including the *Rude Mechanicals*. In 1988, he met Niamh Morris, a member of UCD Dramsoc, and their friendship blossomed, leading to their marriage on 2nd January 1991 in St Paul's, Glenageary. They chose that date as many of their friends, now working abroad, were home for the Christmas holidays. The happy couple lived in Tram Cottages in Dalkey, before moving to a fixer-upper on Albert Road, Dun Laoghaire.

5. RESEARCH

Back in 1983, David's new Department appeared to be broke and to have no equipment. The only people who had research money were Andrew and John Fitz, the former from European grants, and the latter for his work on noise and vibrations. David hit on the idea of doing literature surveys and compiling data and was greatly helped by Garry Lyons who digitised graphs from research papers. This resulted in *A Compendium of Fatigue Thresholds and Crack Propagation Rates, Vols. 1 & 2,* and some theory papers on fatigue. David became a chartered member of the Institution of Engineers of Ireland in 1985.

Brendan McCormack returned from the US and began working for orthopaedic surgeon, Jimmy Sheehan, in the Blackrock Clinic. Brendan contacted David to discuss his ideas about reinforcing the cement used to secure femoral stems in hip replacement surgery. Blackrock Clinic and the Government provided funding for MSc students, and the first of these was

Danny Shuter, which led to a fatigue paper memorably authored by Hunter, Shuter and Taylor! David has supervised 20 MSc and MCh theses to date (Table 1).

Table 1: MSc and MCh Theses supervised by David Taylor

1) Danny Shuter (1986) *Fatigue Behaviour of Rough Surfaces* MSc.
2) Jean-Marc Moalic (1987) *Fatigue Behaviour of Fibre Reinforced Polymethylmethacrylate* MSc
3) Fergus Clarke (1988) *Fibre Reinforcement of Bone Cement for Hip Joint Prostheses* MSc
4) Orla Clancy (1988) *The Influence of Rough Surfaces on the Fatigue Life of a Metal* MSc
5) Sean McVeigh (1990) *An Analysis of Long-Term Failure in Polymer Products* MSc
6) Brian O'Brien (1991) *The Design of an Isoelastic Hip Prosthesis* MSc
7) Colm Martin (1991) *Development of an Artificial Hip Joint Using a Modulus Matched Material* MSc
8) Gerard Henn (1992) *Mechanical Assessment of a Composite Material for Orthopaedic Applications* MSc
9) Simon Toland (1994) *External Fixation* MSc
10) Elaine Smith (1995) *Processing of Silicone Breast Implants* MSc
11) Catherine Johnston (1995) *Fatigue Behaviour of Manufactured Surfaces* MSc
12) Thomas Culleton (1995) *Mechanical Simulation of the Artificial Hip Joint* MSc
13) Fergus McMahon (1996) *Polymerisation of Chitin* MSc
14) Martin O'Sullivan (1999) *Assessment of Shock-Absorbing Polymers for Artificial Knee Joints* MSc
15) Brendan Fay (1999) *Growth of Short Fatigue Cracks* MSc
16) Niall Barrett (1999) *Fatigue in Welded Joints* MSc
17) Kirti Moholkar (2000) *A New and Safer Technique of Harvesting Patellar Bone Plug During Cruciate Ligament Reconstruction* MCh
18) H.Yoshino (2000) *Bone Toughness Assessment* MSc
19) Peter O'Reilly (2001) *Bone Fatigue in Torsion* MSc
20) Victor Chaves (2002) *Critical Distance Theory of Metal Fatigue* MSc
21) Amanda Schmidt (2020) *Erosion of Tissue by Surgical Mesh* MSc

David's first PhD student was Robert Li, and he has supervised or co-supervised 35 PhD theses in all (Table 2). The second PhD combined materials and health sciences – Robbie McConnell's project on adhesive dental bridges in 1987 – and Robbie went on to be Professor of Dentistry at UCC. David was elected a Fellow of Trinity College Dublin in 1989 and promoted to Associate Professor in 1992.

Table 2: PhD Theses supervised/co-supervised by David Taylor

1) Robert Li (1985) *A Study of Certain Classes of Constitutive Equations for Anisotropic Solid Materials*
2) Robert McConnell (1987) *A Study of the Dental Adhesive Bridge*
3) Patrick Prendergast (1991) *A Structural Analysis of the Artificial Hip Joint*
4) Edward Commins (1992) *A Comparative Fatigue and Corrosion Fatigue Assessment*
5) Michael Kearney (1992) *Non-Destructive Measurement of Shot Peening*
6) Li Jianchun (1993) *A Study of Short Fatigue Cracks*
7) Lisa Looney (1994) *The Effect of High-Pressure Hydrogen on the Creep Fracture of Ferritic Steel Components*
8) Brian McNamara (1995) *Simulation and Prediction of Bone Remodelling*
9) Clive Lee (1995) *Functional Adaptation in Compact Bone*
10) Peter Byrne (1996) *The Effect of Surface Roughness on Fatigue*
11) Manus O'Donnell (1996) *The Effect of Cyclic Thermal Fatigue/Creep on Crack Growth*
12) Barry Shreiber (1996) *Fracture Toughness of Alumina Ceramics*
13) John Cogan (1998) *Expert Systems in Medicine*
14) Cathal Walsh (1999) *Statistical Analysis of Short Fatigue Cracks*
15) Wang Ge (1999) *Use of Finite Element Analysis in Fatigue Prediction*
16) Fergal O'Brien (2000) *Microcracks and the Fatigue Behaviour of Compact Bone*
17) Finbar Dolan (2002) *Fatigue of Polymers*
18) Danny Bellett (2002) *Fatigue in Three-Dimensional Stress Concentrations*
19) Jan Hazenberg (2004) *The Cellular Transducer in Damage-Stimulated Bone Remodelling*
20) Susanne Weirsma (2004) *Fatigue and Fracture of MicroComponents*
21) Matthew Mercy (2006) *Failure Mechanisms in Bone – a Mechanical and Histological Study*
22) Cormac Brady (2006) *Biomechanics of the Temperomandibular Joint*
23) Oran Kennedy (2007) *The Effect of Bone Turnover in Bone Quality and Material Properties*
24) Saeid Kasiri (2008) *Modelling the Cutting Process in Bone*
25) David Hoey (2009) *Fatigue in Bone Cement*
26) James Dwan (2011) *Diamond-Based Cutting Materials*
27) Gerardo Presbitero (2011) *Microdamage in Bone*
28) Lauren Mulcahy (2012) *Response of Osteocyte Networks to Microdamage*
29) Pietro Tisbo (2013) *Computer Simulation of Bone Remodelling and Repair*
30) Clodagh Dooley (2013) *Mechanical Behaviour of Osteocyte Networks*

31) Nick Mahony (2013) *Characterisation of Osteoporosis*
32) John O'Rourke (2015) *Active Implantable Pulse Generator's Header System Structural Adhesive Bond Durability Study*
33) Eoin Parle (2016) *Investigations into the Mechanical Properties of Insect Cuticle*
34) Maeve O'Neill (2019) *Insect Biomechanics*
35) Tim Hone (2022) *Biomechanics of Plant Stem*

Based on these 55 theses – Martin Luther managed 95 - and other projects, David has published 4 books and 250 research articles, and his h index is 40 (Fig. 7).

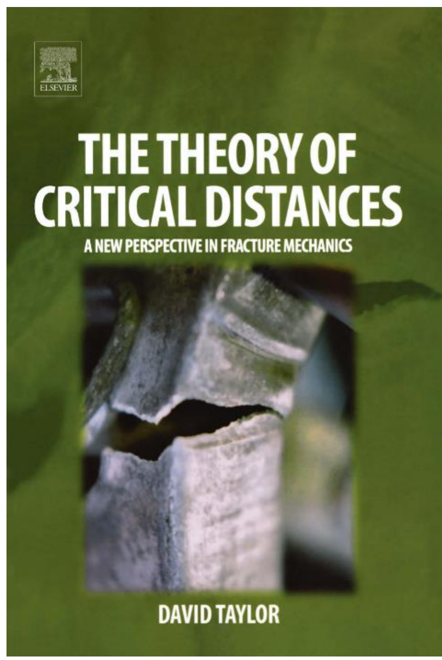

Figure 7. David's book *The Theory of Critical Distances* (2007).

David was awarded his ScD for published work by Cambridge University in 2003, a Personal Chair in Trinity College Dublin as Professor of Materials Engineering in 2008 and was elected a Member of the Royal Irish Academy (RIA) in 2009, an Honorary Member of the Italian Group of Fracture in 2009, and won the Zwick Science Award in 2011.

6. SOME REFLECTIONS

Reflection 1

– a former research student from North Wexford writes:

My final year project was on non-linear vibrations with Henry Rice, and it hooked me on research. When David put a message on the departmental notice board that he was offering a funded MSc by research, I was quick to drop into his office in Lincoln Place to let him know I was interested. Moving from mechanical to materials was like changing political affiliations, but Henry gave me the thumbs up. David had arranged for me to use a mainframe computer and finite element analysis package called PAFEC in the offices of EOLAS (now Enterprise Ireland) in Glasnevin. I spent my first year there. I would come into the Parsons Building every few weeks for lab meetings. David's group was the biggest in the department and these meetings with David where we all contributed ideas made us all feel like real researchers! David was a lecturer then and very much the up-and-coming young research star. His supervision style was to encourage debate, and my MSc was to be a stress analysis of the polymer grouting a hip prosthesis into the femur. The stress analysis of bone cement, while technically challenging, was conceptually straightforward, and we got more interested in the stress/strain patterns in the bone, and why bone around a prosthesis 'remodels' its shape over time. 'Why don't you stay on and do a PhD in this?' said David, and in that he fulfilled, what in my opinion, is one of the key roles of the supervisor - leading the student onto a worthy topic. We went on to develop an accumulative damage theory of remodelling. I will always be grateful to David for giving a 21-year-old a chance to do research in 1987.

Reflection 2

– a former research student from South Dublin writes:

As a medical graduate recently appointed to a lectureship in anatomy, I needed to undertake research to avoid getting stuck. In early 1990, orthopaedic surgeon John Corrigan suggested that I talk with David about an ankle biomechanics project, so I went to see him in his office overlooking Lincoln Place. Our conversation mainly concerned a very smart PhD student of his, then in Italy, and a finite element model of how fatigue induced microdamage caused bones to remodel. My mission, should I decide to accept it, was to find some experimental evidence for this. It would have been much easier, I thought at the time, if David had just told me what to do. Instead, there was a Socratic approach, with more questions than answers, and lots of 'Ah wells!'. It is painful getting graduate students to think for themselves, but Dave bore it well. Real life intervened in the form of teaching commitments, as opposed to a homework-eating dog, but he only became overtly irritated once, telling me not to come back until I had actually done something. It seemed to do the trick. After a lot of reading, a visit to the Natural History Museum to look at skeletons, and a grant from the HRB, I ended up with a flock of sheep on the UCD farm and histological evidence of both microdamage and bone remodelling – *Eureka*! However, his light touch approach occasionally let us down. When I collected my External Examiner from the airport and drove him to the Royal Marine Hotel, it transpired that David had omitted to book him a room. 'Do you have any available?' I asked. 'Yes', they said. 'Then please give him a nice one'. As I was about to get into my car, the Extern appeared at a first-floor window and shouted ‘Come up and see – they’ve given me the bridal suite!’.

7. BIOENGINEERING IN IRELAND…AND ABROAD

Research group meetings involved not only David and his students, but Brendan McCormack’s from UCD, and others from further afield. In 1985, David founded and chaired the Bioengineering Centre in Trinity, still going strong as the Trinity Centre for Biomedical Engineering, while the Department changed its name to Mechanical, Manufacturing and Biomedical Engineering before he retired (Fig. 8).

Figure 8. Trinity Centre for Biomedical Engineering.

David and Brendan also established the Bioengineering Design Forum which met in hospitals on Saturday mornings to engage with clinicians and discuss engineering solutions to medical problems. This was formalised as the Section of Bioengineering of the Royal Academy of Medicine in Ireland (RAMI) in 1994, with David as its first President and Alun Carr as Secretary [1]. In 1995, David founded an annual meeting, *Bioengineering in Ireland*, which met for a number of years in Tulfarris House, near Blessington (Fig. 9).

Figure 9. Tulfarris House, Co Wicklow.

Of these, the 1996 meeting, when we were snowed in, and the 1999 one, when Ulster won the Heineken Cup, were particularly memorable. In 1998, BinI was a joint meeting with The Ulster Biomedical Engineering Society (TUBES). The Good Friday Agreement was a milestone that year and TUBES was one of two organisations that replaced 'Ulster' with 'Northern Ireland' in its name, the other being the police service. We also had a joint meeting with the British Orthopaedic Research Society (BORS) and, in 2000, with the European Society for Biomechanics (ESB). Since then, meetings have been held all around Ireland. Other highlights have been the fancy-dress dinners, of which David is an enthusiastic supporter. Initially, there was a prize for the 'best in show', for which a RAMI bronze medal was awarded, and an invited Samuel Haughton Lecture, for which a RAMI silver medal has been awarded since 1999. David has won both - bronze in 1998 and silver in 2006 – and was elected a Fellow of the Royal Academy of Medicine in Ireland (Fig. 10).

Figure 10. Haughton Silver Medal, RAMI.

David's Haughton Lecture *Telling Stories About Bone* was later published by RAMI in the *Irish Journal of Medical Science* under the more formal title of *Theoretical Modelling in Bioengineering* [2]. In 2022, Bioengineering in Ireland takes place in Galway in May, the 27th conference in a row.

David enjoys travelling, whether for group-bonding in Killary Adventure Centre or conferences in Greece and Regensburg (Fig. 11). David is particularly fond of Italy, where he has spent sabbaticals in Politecnico di Torino as Visiting Professor (1997, 2001, 2006), and in the University of Ferrara as Distinguished Visiting Professor (2007-2011). He and Niamh have a house in the Italian Alps.

Figure 11. *Abbey of Weltenberg,* watercolour by D. Taylor (2007).

David has served on the editorial boards of the *International Journal of Fatigue, Structural Durability and Health Monitoring, Engineering Failure Analysis* and *Frattura ed Integrita Strutturale,* and as guest editor for *Fatigue and Fracture of Engineering Materials and Structures, International Journal of Fatigue* and *Engineering Fracture Mechanics.* From 2007-2015, he took the plunge as founder and Editor-in-Chief of *Journal of the Mechanical Behavior of Biomedical Materials,* kindly including Clive Lee, Fergal O'Brien, Paddy Prendergast and Ciaran Simms on his editorial board. Happily, the editorial board meetings were in Hawaii (Fig. 12).

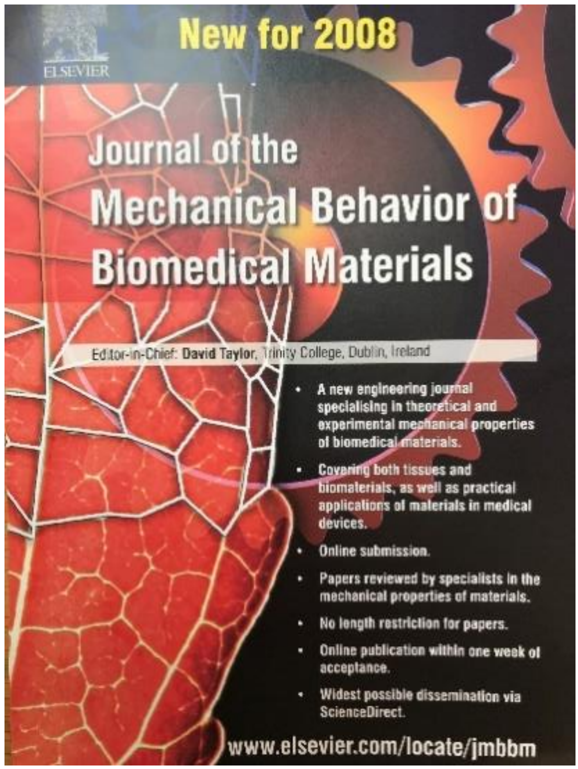

Figure 12. The launch of JMBBM.

David has been a Company Director of Medisolve, an expert witness in the law courts, a Director of the Association of Consulting Forensic Engineers (2007-2020) and has served on assessment panels for Engineers Ireland and as Head of the Department of Mechanical and Manufacturing Engineering (2010-2014).

8. MANNERS MAKETH MAN

So how can one sum up David Taylor? As a materials scientist, it is relatively straightforward – one can look at the keywords from his publications listed in his online *Curriculum Vitae* (Table 3).

Table 3: Keywords from David's publications

316L STAINLESS STEEL; 3D; ACCIDENT INVESTIGATIONS; ACCUMULATION; AUTOGRAFT; AUTOMOTIVE COMPONENTS;

BAYES INFERENCE; BAYESIAN INFERENCE; BEHAVIOR; BETA-LIMIT; BIOENGINEERING; BIOMECHANICS; BONE; BONE ADAPTATION; BONE DAMAGE; BOVINE BONE; CARBON; CAST IRON; CHELATING; CHROMATOGRAPHY; COALESCENCE; COMPACT BONE; COMPONENT; COMPONENTS; CRACKS; CRITICAL DISTANCE; CRUCIATE LIGAMENT RECONSTRUCTION; DAMAGE; DENSITY; DYNAMICS; EVENT; FAILURE; FATIGUE; FATIGUE CRACK PROPAGATION; FATIGUE DAMAGE; FATIGUE LIMIT; FEMORAL CONDYLE FRACTURE; FEMUR; FLUOROCHROME; FORENSIC ENGINEERING; FRACTURE PATH; FRACTURES; HIERARCHICAL MODEL; HIPS; HOLD TIME; IMAGES; INDEX; INTRAMEDULLARY PROSTHESES; MATERIALS TECHNOLOGY; MECHANICAL ENGINEERING; MICRO-CRACKS; MICROCRACK; MICRODAMAGE; NON-PROPAGATING CRACK; NOTCH; NOTCHES; OPERATION; PARIS-ERDOGAN EQUATION; PARTICLE-VOLUME FRACTION; PHYSICS; PLASMAS; PLASTICS; POLYMER COMPOSITE HIGH IMPACT POLYSTYRENE; POROSITY; PREDICTION; PROBABILISTIC ANALYSIS; PROPAGATION; PROSTHESIS COLLAR; RELIABILITY; REMOTE SENSING; REMOVAL; RUBBER PARTICLE SIZE AND PHASE VOLUME TENSILE PROPS; RUPTURE; SHORT FATIGUE CRACKS; SIZE; STRENGTH; TEARING MODES; TFTR; TRANSPORT; UNREAMED FEMORAL NAIL

As a person, it is a little more complex, but keywords are a start. Table 4 lists keywords used by colleagues whom I asked to describe David.

Table 4: Keywords used by David's colleagues

AH WELL; ARTINEER; BAD BRITISH SENSE OF HUMOUR*; BRILLIANT; CALM; CEMENT; COLOURFUL; CRITICAL*; CURIOUS; CULTURED; DETECTIVE; DETERMINED; ECCENTRIC; ECLECTIC; EFFECTIVE; EMERITUS; ENIGMATIC; ENTERTAINING; EUROPEAN; GREAT CRAIC; INDEFATIGABLE; INTUITIVE; KEEPER OF UNUSUAL SPECIMENS~; MECHANARTISTIC; MODEL; MULTI-DISCIPLINED; PATIENT; THOUGHTFUL; WELCOMING; WISE; ZERO STRESS

(*but in a good way; ~ trampoline, hernia mesh, bicycle frame, Samurai sword)

9. CONCLUSIONS

So there you have it – some facts and reflections on David Taylor. We were lucky to get him in 1983, and while others may have approached him with tempting offers to work in the UK or Australia, he has stayed with us as he enjoys the collegiality of Trinity and the pleasant working environment of the Parsons Building (Fig. 13).

Figure 13. Trinity Engineers, New Fellows' Dinner 2022.

But this is only our starter for 10 – the subsequent papers in this *Festschrift* will tell us more about our eccentric, eclectic, effective, emeritus, enigmatic and entertaining European engineer. It is an opportunity to celebrate David's academic career with him, to thank him for all that he has done for us, both individually and collectively, and to wish him a long, happy and healthy career as our Professor Emeritus. If Samuel Haughton was the Father of Irish Biomechanics, then perhaps David is its much-loved Godfather (Fig. 14)?

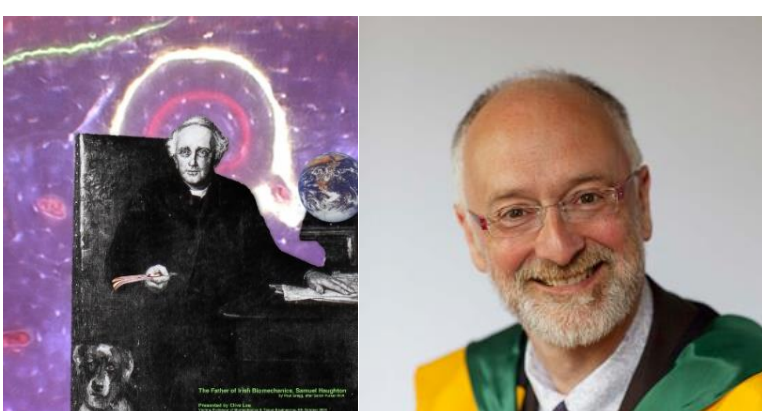

Figure 14. The Father and Godfather of Irish Biomechanics.

10. ACKNOWLEDGEMENTS

I am very grateful to David for discussing his career with me, and to Patrick Prendergast, a former research student from North Wexford, for his reflection and comments. I am greatly indebted to both for their advice and friendship over the past 30 years.

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[2] D. Taylor. Theoretical modelling in bioengineering, 12th Haughton Lecture pf the Royal Academy of Medicine in Ireland. *Ir. J. Med. Sci*. Vol. 177 (2008), 1 – 8.

THEORY OF CRITICAL DISTANCES AND FINITE FATIGUE LIFETIME OF NOTCHED ADDITIVELY MANUFACTURED POLYLACTIDE

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ABSTRACT

In 1999 Prof. David Taylor proposed a novel material length-based approach specifically devised to estimate notch fatigue limits of metallic materials [1]. Nowadays, this very successful fatigue design technique is known as the Theory of Critical Distances (TCD). In 2004 we were awarded an IRCSET Post-Doc fellowship to reformulate (under the supervision of Prof. David Taylor) the TCD to make it suitable for estimating finite fatigue lifetime of notched metallic components [2]. Two decades later, to celebrate Prof. David Taylor's outstanding research achievements, the present paper reviews the work we supervised over the last 6 years [3-6] in order to extend the use of the TCD to the fatigue assessment of notched 3D-printed polylactide (PLA).

1. INTRODUCTION

One of the most relevant peculiarities of additive manufacturing (AM) is that components having complex forms can be fabricated by reaching a very high level of accuracy in terms of both shape and dimensions. As far as the design problem is concerned, the fact that 3D-printed components can contain very complex geometrical features results in localised stress concentration phenomena, with the stress raisers reducing markedly the fatigue strength of the components themselves. Therefore, reliable and straightforward design methodologies are needed to accurately perform the fatigue assessment of additively manufactured (AM) materials.

In this context, certainly the TCD is the most powerful candidate to be employed systematically in industry to design AM components against fatigue because:

- it is successful independent of shape and sharpness of the notch being designed;
- it models the material morphology by using a suitable critical distance to calculate the design stress;
- the relevant stress fields can be determined by modelling the mechanical behaviour of the material under investigation by adopting a simple linear-elastic constitutive law;
- the design stress can be determined by post-processing the results from linear-elastic Finite Element (FE) models, with the same numerical solid models being used to inform the manufacturing process.

In this scenario, the present paper reviews the key features of the TCD-based methodology we have developed and validated to specifically perform the fatigue assessment of notched 3D-printed PLA.

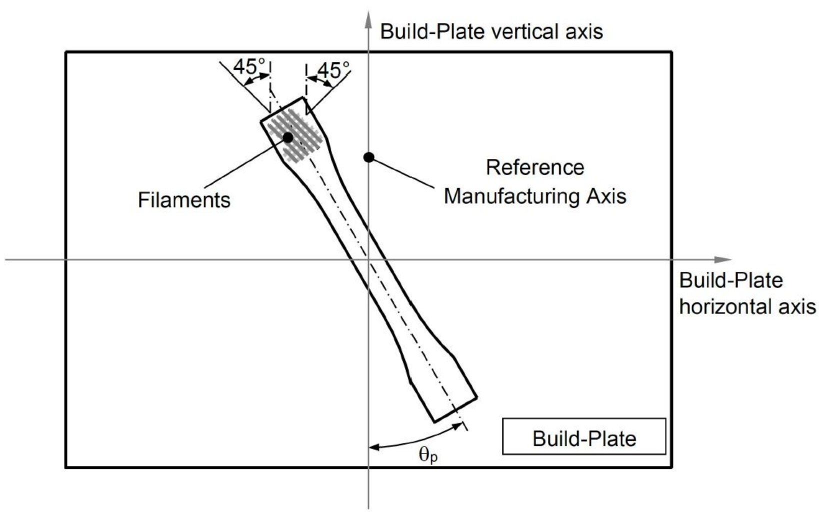

Figure 1. Manufacturing direction and orientation of the deposition filaments.

2. EXPERIMENTAL DETAILS

By using New Verbatim filaments of white PLA with initial diameter of 2.85mm, a large number of plain and notched specimens were additively manufactured via 3D-printer Ultimaker 2 Extended+. The values of the adopted manufacturing parameters were as follows [3-6]: nozzle size equal to 0.4 mm, nozzle temperature to 240ºC, build-plate temperature to 60ºC, layer height to 0.1 mm, shell thickness to 0.4 mm, fill density to 100%, and print speed to 30mm/s. As per Fig. 1, the samples being tested were manufactured flat on the build-plate by making angle θ_p vary in the range 0º-90º. In particular, while the extruded filaments were deposited, layer upon layer, always at ±45º to the build-plate vertical axis (Fig. 1), the angle between the longitudinal axis of the specimens and the build-plate vertical axis was varied so that specimens characterised by different deposition lay-ups could be manufactured (see Fig. 1).

The samples being tested had a thickness in the range 3-5 mm. The un-notched specimens used to investigate the fatigue behaviour of AM PLA had width equal to 6 mm [5]. The notched specimens being manufactured [6] all had net width equal to 6 mm, gross width to 25 mm. The bluntly U-notched specimens had root radius, r_n, equal to 3 mm, whereas the intermediate U-notched specimens had r_n=1 mm. Finally, the sharply V-notched specimens had notch opening angle equal to 35º and r_n=0.15 mm.

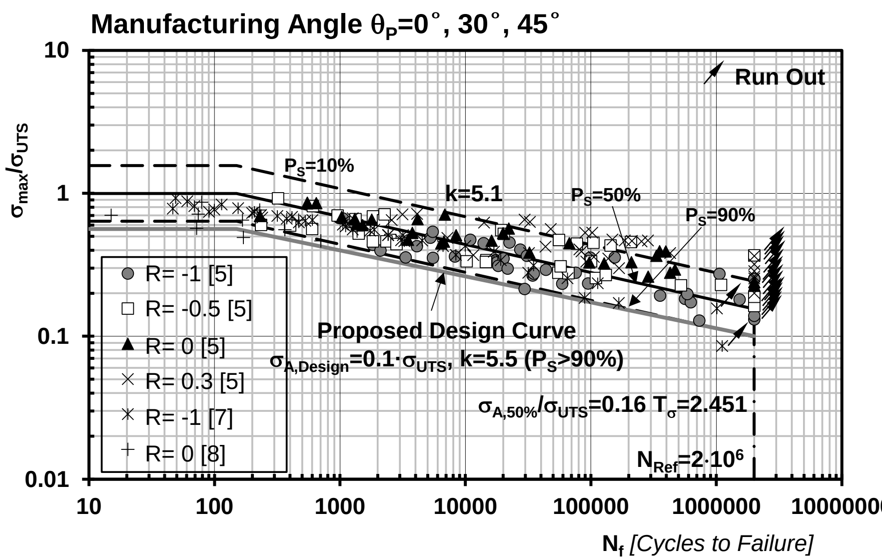

Figure 2. Unifying SN curve recommended to design additively manufactured PLA against fatigue [5].

The fatigue tests [5, 6] were run using an electric fatigue table. Both the plain and notched specimens were tested under sinusoidal axial loading, with the magnitude of the applied axial force being gathered continuously during testing through an axial loading cell. Since the critical cross-sectional area of the specimens was very small, the fatigue tests were run up to the complete breakage of the samples themselves. All the experiments were run at a frequency of 10 Hz. The nominal load ratio, $R=F_{min}/F_{max}$, was set not only equal to -1 (fully-reversed loading), but also larger than -1. The latter loading paths were used to investigate the effect of non-zero mean stresses on the overall fatigue strength of plain/notched 3D-printed PLA. The run-out tests were all stopped at $2{\cdot}10^6$ cycles to failure.

3. FATIGUE BEHAVIOUR OF PLAIN PLA

As far as fatigue assessment is concerned, much experimental evidence [5] suggests that the design problem can be simplified greatly by observing that the maximum stress in the cycle, σ_{max}, is successful in taking into account the detrimental effect of non-zero mean stresses. Further, the manufacturing direction is seen to have little influence on the static mechanical behaviour of AM PLA, with this holding true as long as objects are 3D-printed flat on the build plate [3, 4].

According to these two simplifying hypotheses, if the effect of the raster angle is disregarded and fatigue damage is quantified in terms of σ_{max}, fatigue assessment can then be performed by directly using the unifying scatter band plotted in the SN chart of Fig. 2 [5]. This scatter band was built by post processing not only the data we generated in the Structures Laboratory of the University of Sheffield [5], but also other data taken from the literature [7, 8]. Accordingly, the scatter band seen in Fig. 2 was determined using a large number of experimental results that were generated by testing AM PLA fabricated by making the printing direction vary in the range 0°-90°. Further these un-notched specimens with different material lay-ups were tested under load ratios, $R=\sigma_{min}/\sigma_{max}$, equal to -1, -0.5, 0, and 0.3. In the SN diagram of Fig. 2, N_f is the number of cycles to failure, k is the negative inverse slope, PS is the probability of survival, $\sigma_{MAX,50\%}$ is the maximum value of the endurance limit extrapolated at $N_{Ref}=2\cdot 10^6$ cycles to failure, and T_σ is the scatter ratio of the endurance limit for 90% and 10% probabilities of survival.

The scatter band of Fig. 2 was calculated for P_S equal to 90% and 10% under the hypothesis of a log-normal distribution of the number of cycles to failure for each stress level, with this being done by setting the confidence level invariably equal to 95% [9].

According to the unifying SN curve shown in Fig. 2, whenever it is not possible to determine experimentally the fatigue strength of the specific AM PLA being employed, then fatigue assessment is recommended to be performed (for P_S>90%) by adopting a design curve having negative inverse slope, k, equal to 5.5 and endurance limit, $\sigma_{MAX,Design}$, at $N_{Ref}=2\cdot 10^6$ cycles to failure equal to $0.1\cdot\sigma_{UTS}$ [5].

4. THE TCD TO ESTIMATE FATIGUE LIFETIME OF NOTCHED PLA

The use of the linear-elastic TCD to estimate fatigue lifetime takes as its starting point the assumption that the critical distance value to be used to calculate an effective equivalent stress is a material property whose value increases with decreasing of N_f, i.e. [2]:

$$L_M(N_f) = A \cdot N_f^B \tag{1}$$

where, A and B are material fatigue constants to be determined by running appropriate experiments. In this context, it is important to recall that A and B are different for different materials and different load ratios, but their values do not depend on the features of the notch being assessed [2].

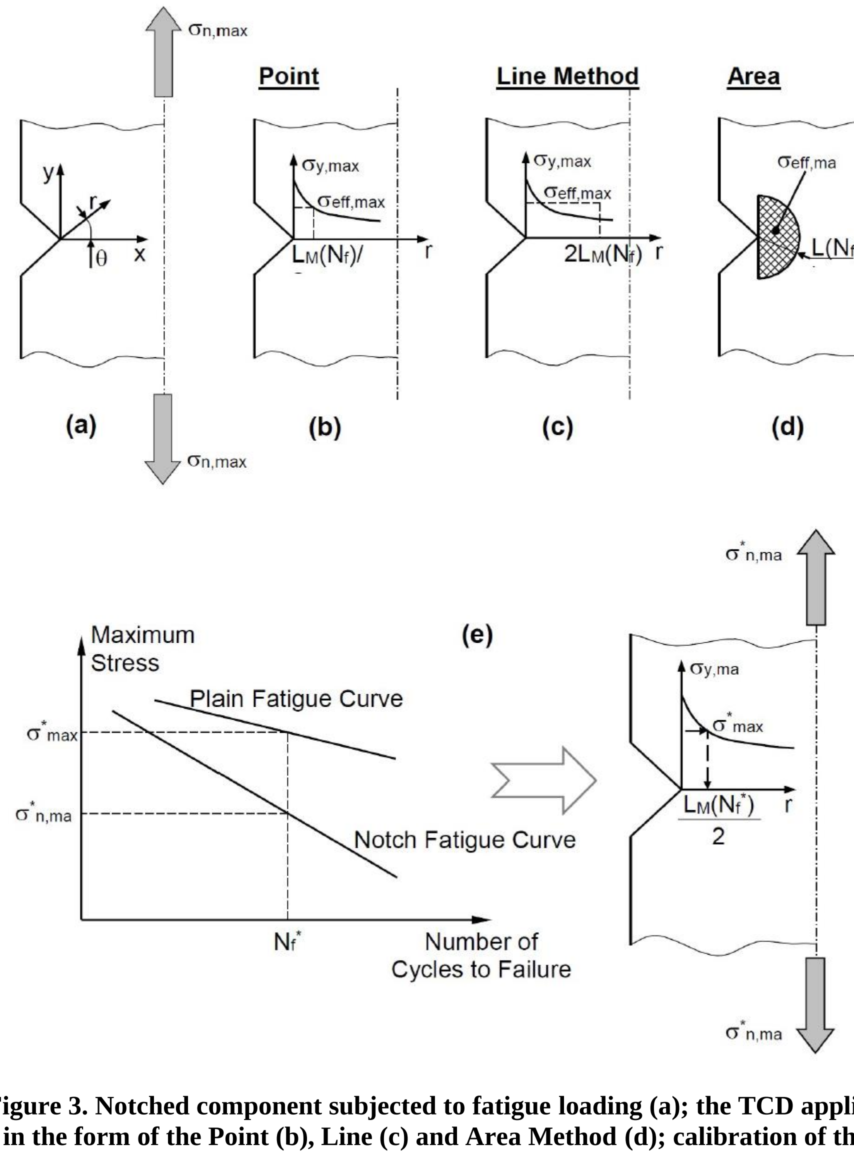

Figure 3. Notched component subjected to fatigue loading (a); the TCD applied in the form of the Point (b), Line (c) and Area Method (d); calibration of the L_M vs. N_f relationship by using two different fatigue curves (e).

If Eq. (1) is assumed to be known for the material being assessed, the TCD can then be formalised in different ways by simply changing the definition of the integration domain used to calculate the maximum value of the effective stress, $\sigma_{eff,max}$.

In particular, if such a stress quantity is estimated according to the Point Method [1], then $\sigma_{eff,max}$ can be calculated as (Figs 3a and 3b) [2, 6]:

$$\sigma_{eff,max} = \sigma_{y,max}\left(\theta = 0°, r = \frac{L(N_f)}{2}\right) \tag{2}$$

Alternatively, $\sigma_{eff,max}$ can also be determined by averaging the maximum value of the linear-elastic stress, $\sigma_{y,max}$, along a line over a distance equal to $2L_M(N_f)$, i.e. (Figs 3a and 3c) [2, 6]:

$$\sigma_{eff,max} = \frac{1}{2 \cdot L_M(N_f)} \int_0^{2 \cdot L_M(N_f)} \sigma_{y,max}(\theta = 0°, r) \cdot dr \tag{3}$$

This formalisation of the TCD is known as the Line Method [1].

Lastly, the maximum value of the effective stress can also be calculated by averaging $\sigma_{1,max}$ over a semi-circular area centred at the notch tip and having radius equal to $L_M(Nf)$ [2, 6]. Such a form of the TCD is known as the Area Method [1] and it can be formalised as follows (Figs 3a and 3d):

$$\sigma_{eff,max} = \frac{4}{\pi L_M^2(N_f)} \int_0^{\frac{\pi}{2}} \int_0^{L_M(N_f)} \sigma_{1,max}(\theta, r) \cdot r \cdot dr \cdot d\theta \tag{4}$$

Finally, independently of the strategy followed to calculate the effective stress, the number of cycles to failure can directly be estimated through the Wöhler curve describing the fatigue behaviour of the parent material the component being assessed is made of, that is [2, 6]:

$$N_f = N_{Ref} \cdot \left(\frac{\sigma_{MAX}}{\sigma_{eff,max}}\right)^k \tag{5}$$

With regard to the use of Eqs (2) to (4) to estimate fatigue lifetime of notched components, it is evident that they have to be applied through appropriate recursive procedures [2], since the number of cycles to failure needed to calculate the critical distance value according to Eq. (1) is, obviously, never known a priori.

Turning to the calibration of power law (1), constants A and B can directly be estimated from the un-notched material fatigue curve and from another fatigue curve determined by testing specimens containing a notch having known profile and known sharpness [2]. This way of estimating constants A and B is explained in Fig. 3e. In more detail, according to the Point Method, given a reference number of cycles to failure, N_f^*, it is easy to calculate the distance from the notch tip, $L_M(N_f)/2$, at which the maximum value of the linear-elastic stress, $\sigma_{y,max}$, equals the value of the maximum stress, σ^*_{max}, that has to be applied to the plain material to break it at N_f^* cycles to failure (Fig. 3e). Therefore, the critical distance value can then be determined for all the N_f values from the low- to the high-cycle fatigue regime, allowing constants A and B to be estimated unambiguously.

To apply the TCD to post-process the notch fatigue results we generated in the Sheffield Structures Laboratory [6], the local linear-elastic stress fields were calculated using commercial FE software ANSYS®. As per the simplifying assumptions made in the previous sections, the solutions were calculated by modelling the AM polymer under investigation as a linear-elastic, homogeneous and isotropic material.

Constant A and B in Eq. (1) for the AM PLA being assessed were determined from the experimental plain fatigue curve as calculated in Ref. [5] for P_S=50% and the fatigue curve determined by testing the sharply notched specimens with r_n=0.15 mm. The calibration process shown in Fig. 3e applied along with the two calibration fatigue curves mentioned above returned the following L_M vs. N_f relationship:

$$L_M(N_f) = 16.4 \cdot N_f^{-0.242} \text{ [mm]} \qquad (6)$$

This power law was then used to post-process the experimental results being generated according to both the Point and the Area Method. In contrast, the Line Method could not be used because the length of the required integration domain in the medium/low-cycle fatigue regime - i.e., $2L(N_f)$ - was larger than half net-width of the specimens.

The fatigue charts of Fig. 4 that plot the $\sigma_{eff,max}$ to σ_{UTS} ratio vs. N_f confirm that the use of the TCD applied in the form of the Point Method and Line Method returned estimates mainly falling within the plain material scatter band. This result is certainly satisfactory since, from a statistical point of view, a predictive method cannot be more accurate than the experimental information used for its calibration.

5. CONCLUSIONS

According to the experimental/theoretical work that we have done in recent years at the University of Sheffield, UK, it is possible to come to the conclusions summarised below, where these conclusions are strictly valid solely for objects of PLA that are 3D-printed flat on the build plate.

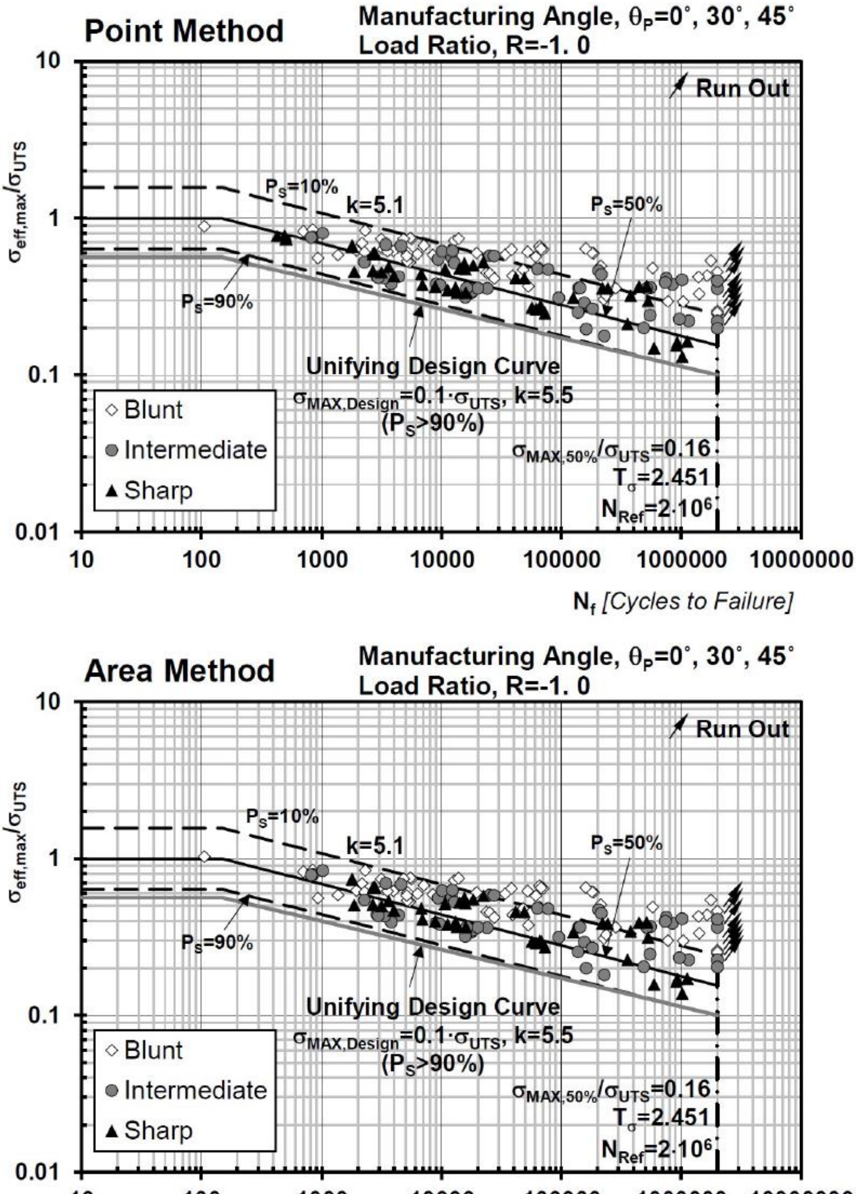

Figure 4. Accuracy of the TCD applied in the form of the Point and Area Method in estimating the fatigue lifetime of the notched specimens of AM PLA tested under axial fatigue loading.

- The mechanical behaviour of AM PLA can be modelled by treating this 3D-printed polymer as a linear-elastic material that is homogenous and isotropic.
- The effect of the printing direction on the overall fatigue strength of plain/notched AM PLA can be neglected with little loss of accuracy.
- The mean stress effect can be taken into account effectively by addressing the design problem in terms of maximum stress in the cycle, with this holding true both in the presence and in the absence of notches.
- If appropriate experiments cannot be run, the fatigue strength of AM PLA can be assessed using a unifying design curve with k=5.5 and $\sigma_{MAX,Design}=0.1\sigma_{UTS}$ (at $2\cdot10^6$ cycles to failure for P_S=90%).
- The TCD is seen to be highly accurate also in assessing notch fatigue strength of AM PLA.

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MY TIME IN TCD WITH DAVID TAYLOR

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ABSTRACT

This contribution starts at my earliest days in Trinity College Dublin (TCD) when I was just beginning to work with David Taylor in the areas of Materials testing and it then progresses through the years, during which I became increasingly involved with his research and with his students.

1. THE EARLY DAYS OF FATIGUE TESTING OF METALS USING IN HOUSE MANUFACTURING EQUIPMENT

I had the pleasure of working with David Taylor for something close to forty years, almost all of my time in TCD. I came to the Department of Mechanical Engineering, as it was then, in November 1982 and Dr. David Taylor, as he was then, followed about six months afterwards, sometime during 1983 as I recall.

1.1 Early Fatigue Testing Machines

We had a benchtop rotating bending fatigue machine at that time mounted on a bench in the workshop (see Fig. 1). These machines were of relatively simple construction and were produced commercially and sold to educational Institutions, but I think that this one may have been constructed as a one off in the workshop in TCD. It is the first fatigue testing machine that I remember Professor Taylor supervising students on and it would have been shortly after he arrived in the Department. This was when I started to be involved with Professor Taylor making fatigue specimens to be used on this machine by his project students. Basically, it was a motor connected by a flexible coupling to a rotating shaft which was supported on four self-aligning Plummer block bearings. The shaft was in two halves with the specimen having threaded ends joining the two halves together at the centre. The outer two Plummer blocks were on fixed supports as was the electric motor but the inner two Plummer block bearings on each side of the specimen were mounted on a platform which was suspended and could be weighed down under the action of a column of weights attached to its underside. This meant that the whole shaft was in a state of bending when the weights were applied to the underside of the inner two bearings.

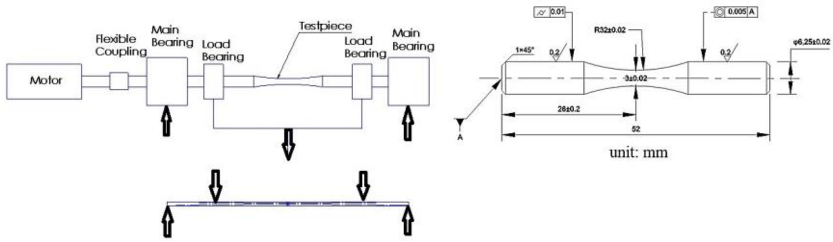


Figure 1. Schematic of Rotating Bending Fatigue Machine.

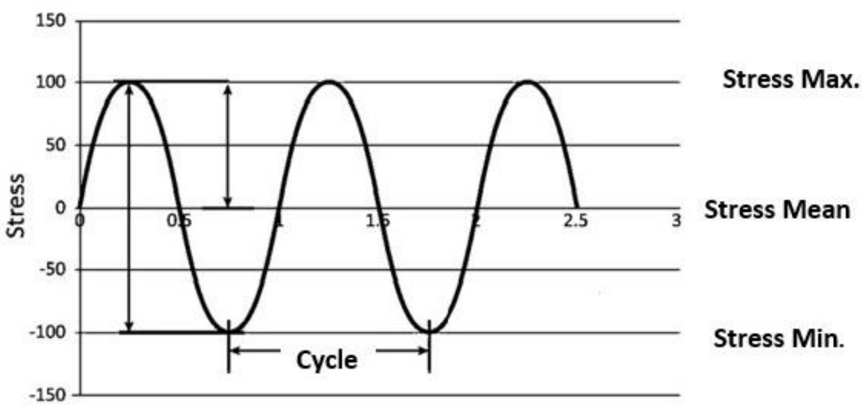


Figure 2. Illustration of Alternating Stress Cycle.

So, when the shaft was in a state of bend the top surface of the specimen was in compression whilst the underside was in tension. If the shaft was rotated through 180 degrees, the stresses were reversed meaning that the portion of the specimen that was previously in compression was now in tension and vice versa (Fig.2). This meant that an alternating stress cycle could be produced simply by rotating the shaft. In normal operation the motor would rotate the shaft at 1500 rpm. producing a high frequency alternating stress state in the specimen which was high frequency fatigue testing. There was a tachometer connected to the right-hand end of the shaft which served to record the number of cycles to failure.

This machine was used for a number of years for final year project students and postgraduate students working under David to fatigue test different materials and at the time I was making the specimens for the students and also advising them on testing protocols and specimen design.

1.2 Other Early Fatigue Machines

A variety of other simple construction fatigue testing machines were made in house in the workshop to test metal specimens of different geometries and in different testing modes one of which I designed and constructed myself as part of my Technician Diploma project in 1984 and is shown in Figure 3.

I had been searching for a project to use for my Technician Diploma and I asked David for suggestions, and he suggested designing and building a machine that would fatigue the sort of specimens of aluminium bronze that he had worked on during his Ph.D.

In the machine that I designed and constructed a cuboid specimen was clamped at one end of the machine and connected by a coupling to a lever arm which was then oscillated at one point through the action of an eccentric cam bearing on a disc rotated by an electric motor. In this way rotational motion of the motor was converted into linear displacement of the lever arm which in turn flexed the specimen basically creating a dynamic bending fatigue machine.

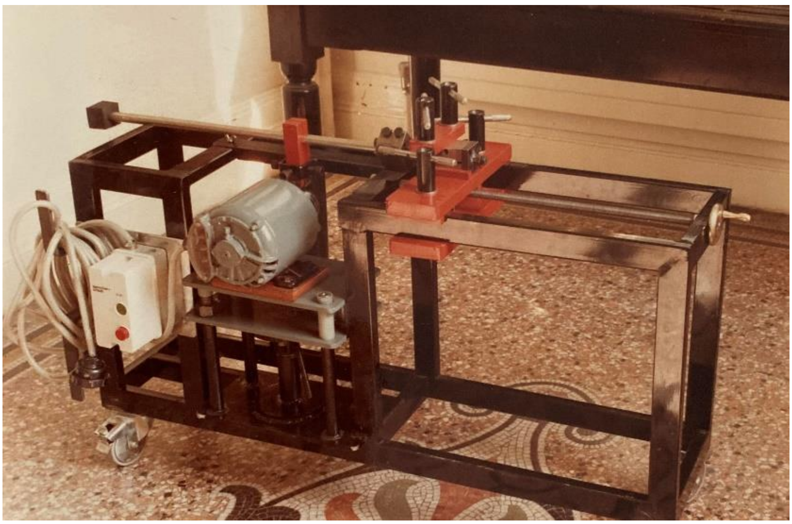


Figure 3. The Oscillating Cantilever fatigue machine [5].

2. MOVING TO TESTING OF BIOMATERIALS USING IN HOUSE MANUFACTURED EQUIPMENT

A few years after this around 1988 -1989 Dr. Brendan Mc Cormack was studying for a Ph.D under David and he had a requirement to fatigue test bone cement as bone cement was being used for cementing hip prostheses in human hip replacements. At this time Dr McCormack was doing collaborative Research with Mr Sheehan the renowned orthopaedic surgeon. This would mark a new departure for us, as up until that point we had only tested metal specimens in fatigue.

It was decided that a fatigue rig would need to be designed and constructed to test samples of bone cement in different configurations. A number of meetings took place between myself, David, Brendan and Mr Alan Reid the Senior Experimental Officer in the Department at the time. A final design strategy was decided upon and Alan designed a simple small bench top machine that would test cuboids of bone cement in four point bending fatigue using compressed air as the power source. Using Alan's drawings, I manufactured this testing rig in the workshop and it proved to work successfully to fatigue test the specimens.

It was then decided to manufacture six of these simple testing rigs in the workshop so that six specimens could be tested simultaneously, and this was done. The rigs themselves took up very little bench space as each one was of cylindrical construction and measured approximately 100mm in diameter and 150mm in height (Fig. 4). They were constructed of mild steel and were simple reciprocating four-point bend mechanisms using compressed air as the power source. Once again, a simple counting mechanism was used to count the cycles to failure of the specimens. The rigs were situated in the basement of the building away from the general population so as not to disturb people.

At that time, I was attending meetings with David and Brendan to discuss testing options. Different configurations of bone cement were compared using these rigs with various reinforcement techniques being employed to reinforce the bone cement. A number of research papers were produced from the tests carried out on these rigs at that time.

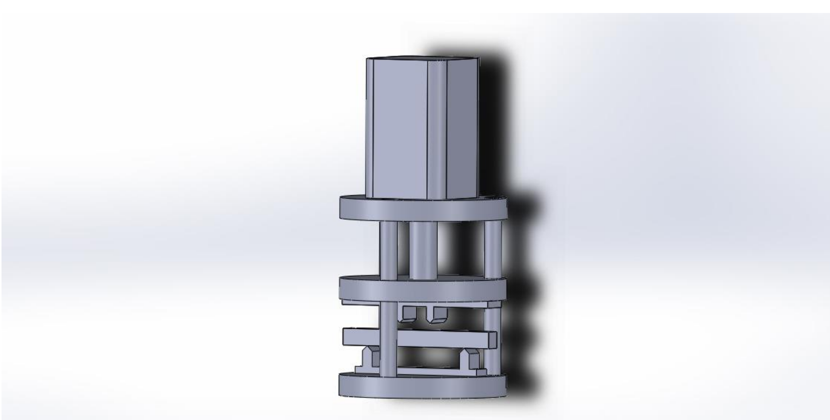


Figure 4. Pneumatic Operated Four Point Bend fatigue rig for testing Bone Cement samples.

3. THE ARRIVAL OF THE HIGH FREQUENCY FATIGUE TESTING INSTRON MACHINES

Sometime around 1995 David Taylor was successful in obtaining a research grant which enabled him to purchase two state of the art Hydraulic Fatigue

Testing machines (See Fig. 5). I was asked to setup and install these machines in the Materials Testing laboratory which was in Lincoln Place at the time.

This was a major advancement as these were highly sophisticated machines in comparison to what we had been using up until now for Fatigue testing research. As time was progressing, I was becoming increasingly involved with David's research. Prior to this I had been mostly involved with the research of Prof. John Monaghan and we had been working together in research into machinability of composites.

After I had installed the hydraulic circuitry and power pack for the Instron machines and had set up the machines in the Materials Testing laboratory I was assigned to take full responsibility for this laboratory and all of its equipment and also the Metallography and Microscopy laboratories adjoining it in Lincoln Place.

This now further cemented the working relationship between myself and David as he was the academic mostly involved in these laboratories along with Professor Monaghan. I was also involved with almost all of his final year project, and postgraduate students assisting them with ideas and teaching them how to use the various pieces of equipment.

There were countless projects over the years, but some stand out more than others because of the nature of the testing. One such project was for a Master's student by name of Catherine Johnston who was conducting research into the effects of electro-discharge machining on the fatigue performance of Inconel 718. There was a requirement to conduct fatigue tests on Inconel specimens at very low temperatures. Catherine and I had meetings with David to discuss how to achieve these low temperatures and David suggested using liquid nitrogen.

One thing that I always appreciated about working with David was that he was always keen to make suggestions at meetings about a testing strategy, but he would then "give me my head" so to speak to implement that strategy. I knew that I could always refer to him for advice, but he would wait for me to do that and allow me autonomy to get on with the job in hand.

Catherine needed to test cuboid specimens in four-point bend in fatigue so I manufactured a double walled stainless-steel flask with temperature insulation material between the walls that would surround the specimen during testing and would act as a reservoir for the liquid nitrogen. Liquid nitrogen vaporises very easily at room temperature and more so because we were agitating it due to the hydraulic actuator of the machine cycling up and down at 20 cycles per second. It was impossible to enclose the top surface of the flask completely, so we had to continuously top up the nitrogen decanting from a 20 Litre dewar while we were fully togged out with head shields and temperature resistant gloves (see Figure 5),

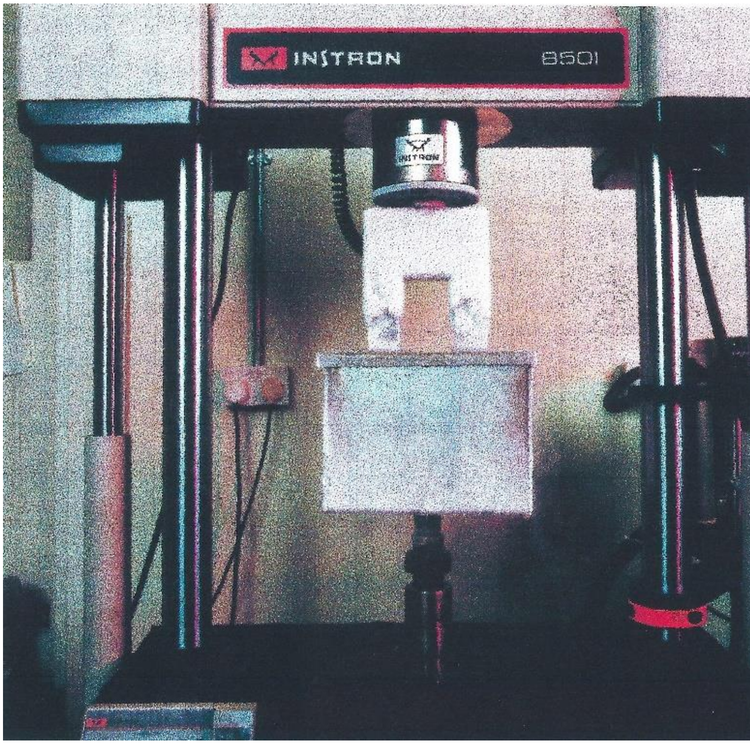


Figure 5. Four Point Bend Setup for testing Inconel 718 in Liquid Nitrogen [8].

4. STARTING TO TEST BONE SAMPLES IN FATIGUE

Up until this time we had conducted tests on bone cement, and we had also started to do some static tests on bone, but Bioengineering was still really in it's infancy in the mid-nineties in our Department. However, then it was decided to conduct compression fatigue tests on bone using the hydraulic Instron testing machines. This was around 1998 to 1999.

Fergal O'Brien was the first to carry out these tests for his Ph.D. project which was supervised by David and Professor Clive Lee.

First the bone samples had to be machined to a regular shape for testing. It was necessary to take core samples of cortical bone from bovine tibiae which were procured from F.X. Buckley's butchers. Then I would take these core samples to the CNC lathe and machine them into dumbbell samples for compressive fatigue tests.

At first, I was machining these bone samples on the large CNC lathe that was in the workshop (see Figs. 6 &7) [6]. At a later stage I found a small benchtop CNC machine on sale that was the type used by secondary schools for demonstrations and David agreed to purchase it for the purpose of machining bone.

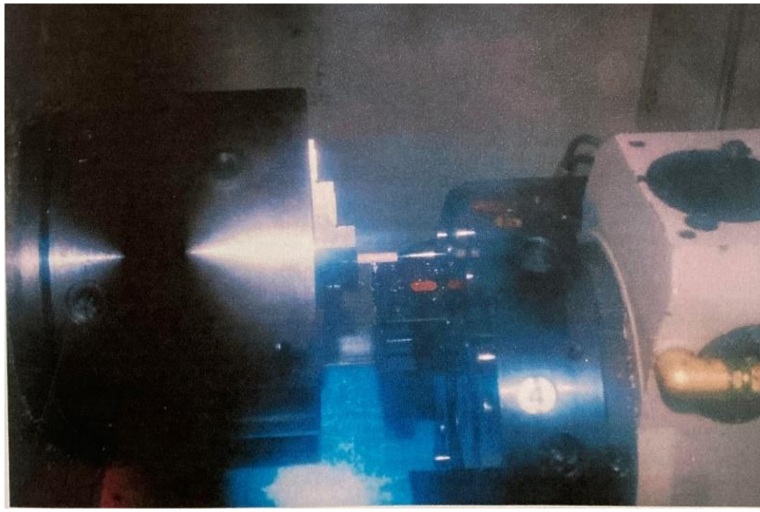


Figure 6. Machining a Bovine Cortical bone dumbbell specimen in the CNC lathe [6].

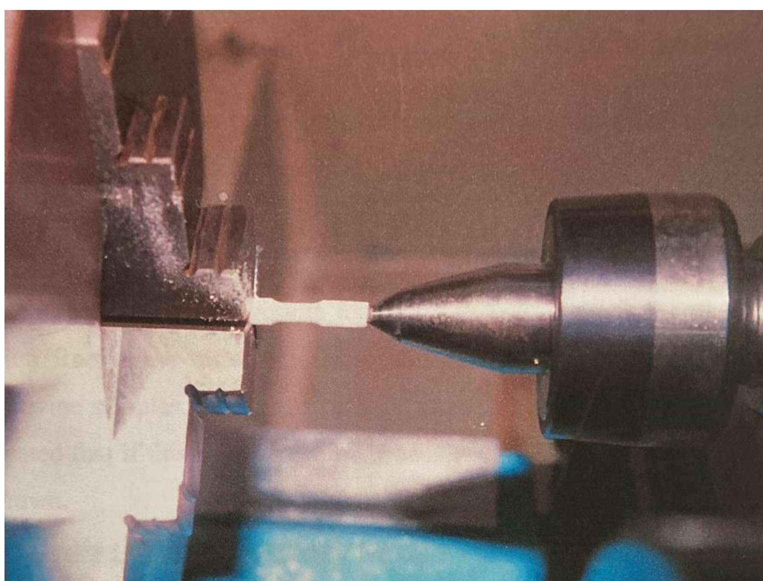


Figure 7. Close up of the same specimen after machining [6].

5. MASTER OF SCIENCE BY RESEARCH SUPERVISED BY DAVID

In 2000 I embarked on a Master of Science thesis by Research under Professor David Taylor entitled ‘Torsional Fatigue of Cortical Bone’. I was to use a rig in the Instron 1341 machine that would convert the linear displacement of the actuator into rotational displacement of a bone specimen.

At first I started with whole chicken metatarsal bones (see Fig. 9) and after testing those for a period I progressed to testing machined dumbbells of bovine cortical bone. It was important that we had pure torsion so the rig had to allow the bone to physically shorten as it was twisted and this was achieved using a sliding plate mounted on linear bearings (see Figs. 8 & 9) [1].

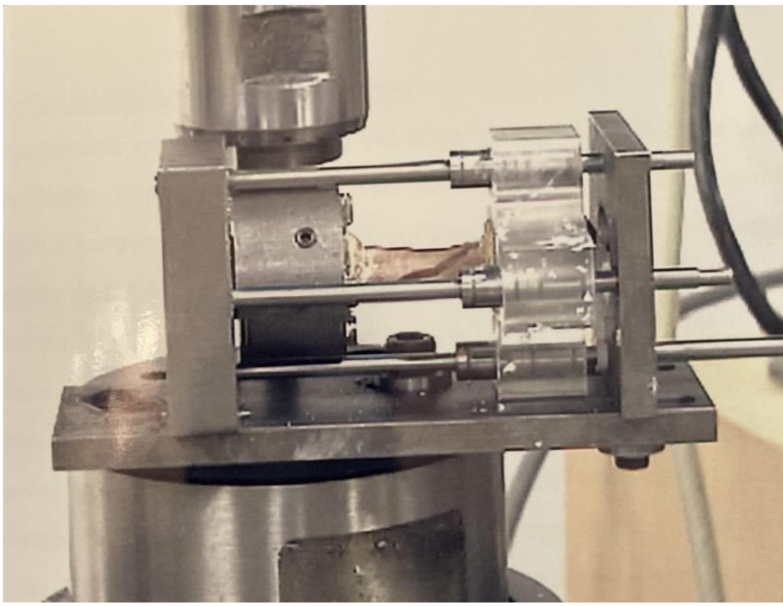


Figure 8. Chicken Metatarsal bone with torsional fracture in the Torsion rig on the Instron machine [1].

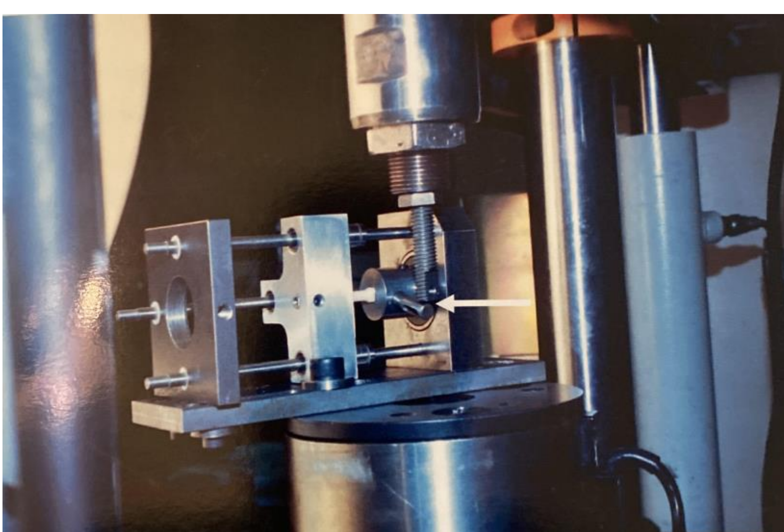


Figure 9. Bovine Cortical Bone in Torsion Rig showing method of load application [1].

6. TESTING OF OTHER MATERIALS WITH DAVID TAYLOR

6.1 Testing of Egg Shells

David was always interested in testing novel materials and in more recent years he looked at the structural properties of materials as diverse as bamboo and eggshell.

The study of the eggshell was an attempt to learn from nature's design how a desirable combination of properties could be achieved i.e. low fracture toughness with high Young's modulus. Free range hen eggs procured from a supermarket were tested in the bench mounted Instron 3366. The internal contents of the eggs were removed before testing by drilling a small hole in each end of the egg and blowing with compressed air. We devised a novel testing procedure which relied on the fact that, if a thin-walled sphere is loaded in axial compression, a simple biaxial stress state arises near its equator. A test rig was designed with the aim of applying axial compression in such a way as to avoid failure occurring at the loading points (see Fig. 10) [2].

We also wanted to create a hole or notch at the midline or equator of the egg so that it would fail from that defect and consequently we could calculate the fracture toughness of the eggshell. To do this we drilled a range of holes on the midline of different eggs ranging from 0.25mm to 2.5mm. We also were able to create notches by first drilling a small hole and then using a needle file to change the geometry of the hole. This study provided adequate scope for a number of final year projects and also a research paper published by David and other members of the group [2].

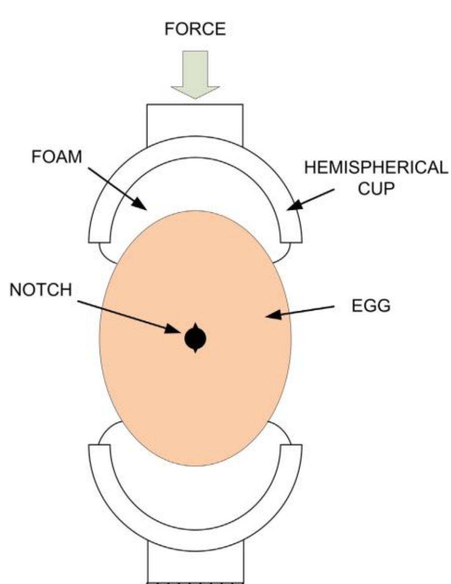


Figure 10. A schematic of the test rig: the egg was contained in two wooden hemispheres, protected with a layer of foam material to prevent local stress [2].

6.2 Testing of Bamboo

The studies on fatigue and failure of bamboo also provided scope for many final year projects and resulted in a number of research papers being published.

David realised that even though bamboo was an important structural material and had been used for many years as a structural material in the construction industry and elsewhere in many parts of the world there was no data available on its fatigue strength. As a result, one of the first studies that we conducted together on bamboo was to test samples in fatigue (see Fig 11 and [3]). Bamboo samples were tested in the Instron 8874 in two modes, along the culm axis and perpendicular to the culm axis. It was discovered relatively quickly that no fatigue behaviour occurs when samples are loaded in axial compression and so the majority of the testing was conducted in diametral loading.

A second area of study was into the joining of bamboo culms as it was realised that this could be a limiting factor in its use in load bearing structures. It was decided to experiment with using machined wooden blocks with hose clamps to join sections of bamboo together. Then the efficacy of the joint could be tested by applying loads in the Instron 5589 to the end of the bamboo section (see Fig. 12 and [4]).

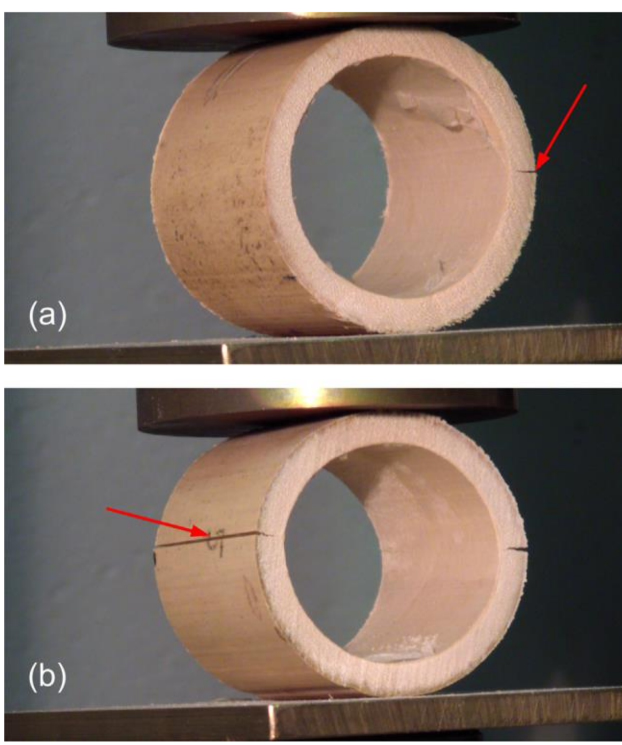
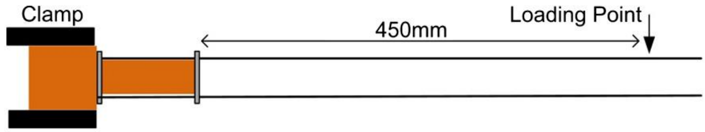
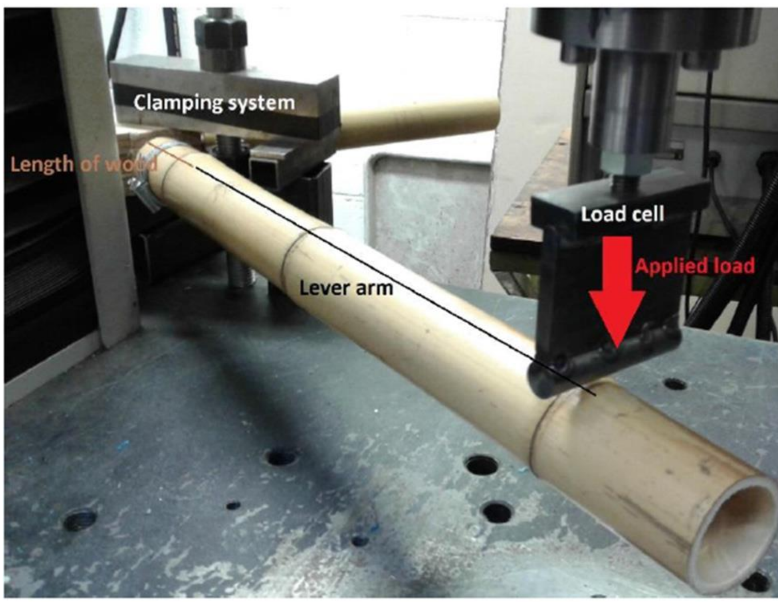


Figure 11. Examples of cracks forming at (a) early stage and (b) late stage during diametral compression tests [3].



(a)



(b)

Fig. 12. Test set-up for the determination of bending strength (a) schematic and (b) photograph of the test in progress [4].

7. CONCLUDING REMARKS

It has been a privilege to work with David during almost all of the time that I was in TCD. The work was always very varied and interesting, and I will always have good memories of my time working with him.

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GREAT CRAIC, NO STRESS/CORROSION

Donal Terry

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ABSTRACT

Thirty-five years ago, I attended when RTE's *Brian Farrell* addressed the *Philosophical Society* at University College Cork. He wondered aloud what the term *philosophical* meant and what it was to *be* philosophical in the context of a whole University society dedicated to that state of mind or attitude. He told the audience that he had been greatly enlightened during a recent visit he described to Moore Street where he overhead two senior lady street traders in conversation. One lady, the complainant, bemoaned her life and the various stresses and strains, disappointments and dilapidations she was subject to in her domestic and family life. Her friend, the respondent, gave sage advice when she told her to "*Be philosophical – just don't think about it*"!

I am reminded of this anecdote when I consider the word "*Academic*". The word is often used to erode, in a less than subtle way, the relevance or significance of the topic under consideration. For example, a person might say "*Ah well, it doesn't matter - it's all a bit academic anyway*". This seems to suggest that the topic at issue has somehow drifted off into a backwater, confused and stagnant, no longer relevant in the fast-flowing confluence of our lives. My dealings with David over the last twenty-five years have served to reverse that implication, and instead to amplify the importance, relevance and influence of academics and academia in what is euphemistically called '*the real world'*. I am eternally grateful to David for his insight and enrichment over that quarter of a century and have often travelled and relied upon the bridge that he builds between the adversarial and contentious world of litigation and the pure and uncorrupted world of data collection, research analysis and conclusion.

1. A COLLEAGUE BY ASSOCIATION

In parallel with David's decades of research and investigations into materials properties, characteristics and (most interestingly), failures inside and outside the University, he was a dedicated and productive member of our professional sub-set of Engineers Ireland, which is the *Association of Consulting Forensic Engineers* (ACFE). He provided education and illumination of the members through many Continuous Professional Development (CPD) presentations given over the years and indeed he sat on the Committee for a great many years, only retiring gracefully recently. His reasoned approach and dedication to the process of data harvesting, research, and analysis before advancing a watertight conclusion, not only contrasts with the style of some lesser practitioners but will be greatly missed as a reminder of scientific discipline in our wider community.

2. ELEMENTARY, MY DEAR WATSON

A visit to David's office at Trinity College always promised to be a pleasant, warm, and welcoming affair. However, it also held the promise of an intriguing view of an Aladdin's cave full of (broken) treasures ranging from buckets to bicycles, prostheses to propellors. He was always generous with his time and insight describing, where he was permitted, the relevant features of an interesting failure. Unlike the often combative world of the commercially minded Forensic Engineer, David did not waste his time trying to show who was the cleverest person in the room. He did not have to. That is invariably why we, aspirationally describing ourselves as his *colleagues*, had come to the mountain to seek his guidance.

That guidance was given freely, without a hint of high-handedness, high-mindedness, or a whiff of the intellectual diva. It was given always in a measured way, with each building brick of his reasoned conclusion laid squarely and firmly on the preceding one to build a solid opinion capable of withstanding the tremors of debate, doubt, or the worst kind of earthquake - ill-informed cross-examination. The structure of his opinion was built only as high or as far as it would go. It was never over-extended beyond the limit of the data which supported it. There were no leaps of faith to unfounded overhangs capable of their own failure in a metaphorical analogy of the work undertaken. Instead, David's calm and measured style of structured research and analysis allows him to engage in *searching* for solutions without *surging* to conclusions, which would inevitably mean skipping necessary steps.

3. AS IF BY MAGIC

One of the most significant elements of work undertaken by David in a case in which I was also involved concerned the mysterious failure of brass components in domestic water installations fitted in hundreds of apartments throughout Dublin during the building boom of the late 1990s and early noughties. Apparently random and occasional failures of these particular brass components which supported a ballcock in a simple water tank led to total and catastrophic failure of the component without warning in 2008. The effect of their failure was to mistakenly "tell" the water system that the tank needed more water. This is a simple function of a ballcock float valve which has operated satisfactorily for over two hundred years (having been patented in 1797). However, this was far from satisfactory as the message sent by the failure was incorrect, the tank was *already* full, and the failure led to surcharge, overflow, and flooding with costly consequences.

Several engineers examined the brass components and considered just what external stimulus could have imposed a force so great as to overcome the established residual strength of the alloy causing failure. An act of vandalism or wanton destruction perhaps? All the more sinister then when one considered the fractured components themselves which showed no signs of physical violence, over-tooling, or other evidence of it being “muscled” or abused. But how else could the established strength and capacity of the material have been overcome by forces other than the application of extraordinary force far beyond those normally achieved in service?

Professor David Taylor examined the components and determined that the particular conditions and characteristics required for the development of *Stress Corrosion Cracking* had indeed been present and therefore the units had failed not because their integral strength was overcome by extraordinary forces, but that the integral strength had been reduced as a result of corrosion and environmental stimuli, weakening and making more brittle what was assumed to be the previously strong and ductile material ultimately to a critical level where it was overcome by stresses either residual to the manufacturing process or imposed in normal service. However, he also demonstrated that the parent material was sub-standard and not constituted to the proper ‘recipe’ (BS 2872 and EN 12164) for that type of brass, but had the appearance of brass. As I advised my clients at the time, it was ‘*brassy, but not brass*’. In short, the *mechanism* of failure was determined as *Stress Corrosion Cracking*, whilst the *cause* of failure was determined as *the sub-standard quality of the material*.

David’s discovery led to the replacement of many hundreds of those items, as yet apparently intact but vulnerable to spontaneous future failure, thus preventing an enormous daisy chain of identical failures within these modern dwellings.

4. EX DUCO (SEMPER UBI SUB UBI)

At the centre of David Taylor’s work is, of course, education. In its purest form and Latin root, an educator has the ability to *lead out*. To lead out of darkness into light, to lead out of ignorance into illumination. David Taylor was, and will continue in retirement no doubt, to be a great leader. He is not the type of leader who beats his breastbone, invokes dead warriors and ancestors, and *drives* his people forward ahead of him. That type of leadership might be described as the “*go on*” protocol. The far more effective and collaborative style of leadership is David’s style. It is true leadership where he advances first, prepares the way and beckons to those following - “*come on*”.

I have no doubt that the great many students who developed under his tutelage hugely benefited from the style of leadership and education demonstrated by David over these years. However, I want it to be clear, that it was not just David's University Undergraduate Students and Post-Graduate Students who benefitted from that education, but also his colleagues and friends whom I am very honoured to represent as a totem in this chapter. To paraphrase Kavanagh in his poem *Raglan Road*, David Taylor was never afraid to disclose "*the secret sign*". He was not precious about the scientific or academic tools used to solve our puzzles. He did not shield them from his colleagues and clients like a young schoolchild might obscure his copybook. He freely gave the tools, and he chose to *teach a man to fish*, rather than *give a man a fish*.

For that, his friendship and wise counsel, we, his colleagues in the Association of Consulting Forensic Engineers (and indeed I expect his other students too), will be eternally grateful. We hope he will find time, in his new 'retired' status to remain active within the field of Forensics and continue to support, illuminate, and educate his colleagues in the Association of Consulting Forensic Engineers, whilst also finding the restful time and space that he, without doubt, has earned. We know you will hold firm to the principle - *Semper Ubi Sub Ubi*.

‘AN EXPERT IS SOME GUY FROM OUT OF TOWN’: THE EMERGING DISCIPLINE OF FORENSIC LEGAL EXPERTISE

Sarah Reid

The Law Library, Four Courts, Dublin
&
Department of Mechanical, Manufacturing, & Biomedical Engineering, Trinity College Dublin.

ABSTRACT

The title of this paper is a quote often attributed to Mark Twain. In actual fact he is reported to have said “*An expert is an ordinary fellow from another town*”. This author prefers the Danish scientist and Nobel laureate Niels Bohr’s view that an expert is *"A person who has made every possible mistake within his or her field."* In respect of Mr. Twain’s view, it could certainly be said to apply to Prof. David Taylor and his work before the Irish Courts in that he is an ‘ordinary fellow’ having shown himself to be truly approachable and welcoming to those not from his academic parish (the present author included). However, as he is involved in ongoing cases before the Courts, it would be inappropriate to pass judgment on the second view and whether he has made every mistake in his field.

In recent years Prof. Taylor has excelled in his discipline and focused his forensic efforts on two distinct medical devices: Metal-on-Metal Hips and Pelvic Mesh devices, which is how I came to work with him. Against that backdrop, this contribution looks at the role of expert evidence in Irish litigation and the functions of an expert before the court. Prof. Taylor has established himself and stands out as a leader in the area of professional, considered and effective witness testimony. When he does eventually retire, his absence will be a great loss to lawyers all over the country, and a blessed day for defendants in multiple jurisdictions.

1. THE ROLE OF EXPERTS IN LITIGATION

1.1 The function of expert evidence

The first point worth making is that expert evidence is merely one part of the evidence in a case. A legal case is made by adducing testimony of first-hand, narrative accounts and expert opinions on the topic at hand and together this evidence forms the basis on which the court can determine whose version of events is more credible. When an issue of controversary arises in a case that is grounded in a specialist topic requiring distinct knowledge (for example the safe mechanical functioning, or otherwise, of a medical device) then the experts are summoned to provide evidence that will assist the court understand the parameters of the science in order to weigh the witnesses narrative accounts against it.

As a barrister, I view experts and their evidence through the prism of my client's claim. I listen to the evidence and cross examine each witness based on my client's assertions. The view from the Bench is not therefore something I can speak to. However, Evan Bell Master of the High Court in Northern Ireland writes of his experience hearing and adjudicating expert evidence in the Irish Judicial Studies Journal [1] and posits four observations: "*Firstly, expert evidence does not 'trump all other evidence'[2]. Secondly, a judge must not consider expert evidence in a vacuum [3]. Thirdly, where there is conflicting expert opinion, a judge should test it against the background of all the other evidence in the case which they accept in order to decide which expert evidence is to be preferred [4] and fourthly, a judge should consider all the evidence in the case, including that of the experts, before making any findings of fact, even provisional ones*.[5]"

What is clear then is that, although experts play a significant role in the context of litigation, they are not necessarily the defining or key player in the case. Further, their task is to provide their evidence regardless of their client's interests and this is a principle that is enshrined in the Irish litigation Rules of the Superior Courts [6] and confirmed recently by Supreme Court in *Sweeney v. VHI* [7] that "*An expert can properly be considered part of the litigation team, but only as an expert, obliged to give their independent opinion, and owing a duty to the Court to do so*."

The conclusions arrived at by 'STEM' oriented experts are mostly singular ones and they can say, with some certainty, that their testing confirms a hypothesis which supports an eventuality claimed in a given case. In contrast to this clean and neat way of thinking, lawyers operate on the humanities side of the brain and apply concepts such as 'foreseeability' and 'on the balance of probabilities' and for this reason, the experts and lawyers' perceptions of the same evidence may, at times, differ.

Having taught alongside Professor Taylor for several years now, one of the most enjoyable aspects of the task has been observing the mechanical engineering students adapt to these loose concepts of foreseeability when they are clearly built and trained for definitive conclusion. In contrast, the law students I lectured are trained to work within the grey areas, seeking out ways to establish something was 'more likely than not' based on the evidence before the Court.

1.2 Providing objective analysis

The expert's task in litigation is to provide objective, professional advice to the court and where there is a conflict on a fundamental point in the case, it is the Judge's task to justify a preference for one expert's evidence over the other. Ordinarily this is done by analysing the underlying material and reasoning of the expert but increasingly we are seeing deep divides among the academic and scientific community on an issue. When this arises, the court must determine the issue imposing liability in the case based on their findings.

In *Loveday v. Renton and another* [8] the court was tasked with determining whether the pertussis vaccine for whooping cough could cause permanent brain damage in young children and the judge's ruling in that regard would have significant consequences for the defendants as well as other medical stakeholders. Expert opinion was deeply divided on the issue and so the court was compelled to comment on the performance of each parties' witnesses. Dr. Robinson for the defendants was commended for the care and precision of his answers which demonstrated '*exceptional clarity of thought and reasoning'*. However, Dr. Wilson's reasoning was deemed difficult to follow. As a result, the court concluded it was more impressed by the '*cogency and quality'* of the reasoning of the defendants' experts and this was significant within the overall findings of the case.

More recently in *St George v. Home Office* [9] the UK Court of Appeal held that it is not sufficient to accept the opinion of one expert over another simply on the grounds that they have given their evidence confidently and, while this is undoubtedly so, it has been my experience that this is, in fact, the crowning feature that determines the prospects of success in a case. It is why I agreed (and relished) the task of teaching Product Liability law to students in the Department of Mechanical, Manufacturing & Biomedical Engineering at Trinity College Dublin. They were the next generation of experts, the ones who would end up in Prof. Taylor's shoes in years to come, the ones I would cross examine and the ones who needed to understand the importance of impartial, well-reasoned and objectively justified conclusions that lawyers and judges would be able to apply to the facts of a case.

1.3 Impartiality of an expert

From the court's perspective, the task at hand is to determine, on the balance of probabilities, whether the plaintiff before them has provided sufficient evidence that the incident occurred, or arose, in the way they claim it did. If so, the question then becomes whether the defendant can be said to be legally responsible for the events that unfolded, such that the plaintiff deserves to be compensated for their loss. Our neighbouring legal jurisdiction, the UK, has compiled a Protocol for the Instruction of Experts to give evidence in Civil Claims (also referred to as 'The Ikarian Reefer principles') which are based upon the decision in *National Justice Compania Naviera SA v. Prudential Life Assurance Co. Ltd*. [10]. It states that: "*An* *expert witness should state the facts or assumptions upon which his opinion is based. He should not omit to consider material facts which could detract from his concluded opinion*".

This is of particular significance in the context of expert evidence when the issue in controversary is an area outside the normal course of litigation (for example a novel medical device, or emerging area of science and technology in which the academic community itself is only beginning to consider). In this context, it is particularly important that both the expert and the court be clear on the parameters and basis of the expert's opinion. In *R v. Turner* [11] Lawton L.J. commented that "*…before a court can assess the value of an opinion it must know the facts upon which it is based. If the expert has been misinformed about the facts or has taken irrelevant facts into consideration or has omitted to consider relevant ones, the opinion is likely to be valueless*".

Mr. Bell [12] in his view from the bench observed that "*an expert report is only as good as the assumptions on which it is based. Where the factual assumptions made by an expert witness are proved wrong, their opinion will be invalidated as a result and, where an expert's conclusions are based on assumptions the reasonable accuracy of which cannot be confirmed by the evidence, then the court is likely to conclude that those conclusions are unacceptably speculative*".

2. NEW AND EMERGING AREAS OF INNOVATION

2.1 Testing the reliability of the science

The last decade has produced unprecedented advancements in new technology and innovation, especially in the field of medical devices, and these have yet to be tested. The courts recognise that there is "*a continuum of reliability in matters of science from near certainty in physical sciences to the far end of the spectrum inhabited by junk science and opinion akin to sorcery or magic"* [13]. When this is so, and in order to avoid "*the perils of unreliable science*" [14] judges firstly consider the admissibility of expert evidence so as to exclude manifestly unreliable science. Secondly, even where expert evidence has passed the admissibility test, judges give less weight to science which appears of lesser reliability. In fact, where expert evidence is given, it is the duty of the experts, "*to furnish the Judge or jury with the necessary scientific criteria for testing the accuracy of their conclusions, so as to enable the court form his own independent judgment by the application of these criteria to the facts proved in evidence*" [15].

As was acknowledged in *R v. Cannings* [16], there are fields of science in which society is still "*at the frontiers of knowledge"* and I think it fair to say all experts acknowledge that future research may well undermine today's accepted wisdom. In this regard in *R v. Holdsworth* [17] the Court of Appeal for England and Wales noted that particular caution was needed where the scientific knowledge of the processes involved is or may be incomplete.

In *Wells v. Ortho Pharmaceutical Corporation* [18] a fundamental conflict arose in the evidence of the expert witnesses as to whether a spermicidal jelly had caused the plaintiff's birth defects. The court held that scientific studies were inconclusive on the issue and as such the judge was forced to make a credibility determination in order to decide the victor in the case. In assessing credibility, the Court considered each expert's training and experience, their testimony in terms of its rationality and internal consistency and each expert's demeanour and tone including biases and/or interests which might have influenced their opinions. This is discussed further in the next section, but this author believes it will feature increasingly in cases of new and emerging areas of innovation where scientific positions have yet to be settled.

3. PERFORMANCE OF AN EXPERT

3.1 Demeanour of the Expert

Although the demeanour of an expert witness is less important than that of a factual witness in a case, it is nonetheless material for the purpose of assessing the value of their evidence. Redmayne [19] notes that research suggests that as expert evidence becomes more complicated, jurors shift their focus and rely on peripheral indicia of reliability and credibility such as the expert's qualifications or demeanour.

It may also be the case that after due consideration of expert testimony, the judge is simply unable to decide the issue otherwise than by impression and demeanour. In *Public Trustee v. The Commonwealth* [20] Mahoney J.A. observed that, not infrequently, the court may not be in a position to decide whether the facts on which a witness relies are true and may not be able to judge the scientific or professional accuracy of the principles. In that setting and when a judgment must be made between the facts and the principles advocated at the trial, the court may not be in a position to give objectively convincing reasons for its choice and may, in the end, have to depend upon the impression which the witness has made.

In *Djedovic v. Gonzales* [21] the Court emphasised that the effect and impact of an expert's evidence depended more on the quality of its reasoning and the scope of its data, than on the expert's 'bearing' in the witness box. The judge in that case observed that good scholarly analysis did not become bad simply because a professor stuttered or fidgeted and observable factors like demeanour and tone of voice were less important in the context of expert witnesses, whose reliability was supposed to be based on their expertise rather than on what they claimed to have witnessed. Judge Easterbrook was concerned that judges often overestimate their ability to distinguish true from false testimony by assessing demeanour as "a form of lie detector without the electrodes and graph paper" and opined that the comprehensiveness and logical consistency of testimony was far more valuable in the circumstances.

3.2 Ability to withstand cross examination

The purpose and process of litigation involves intensive, rigorous testing of evidence (including expert evidence) through cross examination. Questions are put by the opposing party's legal counsel who will themselves have been instructed and guided by their side's expert on the issue. The basis for the expert's opinion, the underlying reasons for same and the grounds upon which they maintain their position are probed without apology. Cross examination therefore seeks to explore and establish any biases or unreliable presumptions that may affect the expert's objectivity or opinions an issue.

As Ormrod L.J. observed in *R v. Bracewell* [22] it is "*…part of counsel's duty to invite witnesses to consider alternative hypotheses and, after examining them in detail, to conclude by asking "Can you exclude the possibility?" The available data may be inadequate to prove scientifically that the alternative hypothesis is false, so the scientific witness will answer 'No I cannot exclude it"* but may continue "*But for all practical purposes it is so unlikely that it can safely be ignored".*

Cross-examination does, however, have its limitations and Muldoon J expressed as much in *Unilever p.l.c. v. Procter & Gamble Inc* [23]: "*Cross examination is said to be the great engine for getting at the truth, but when the unschooled judge cannot perceive the truth, if he or she ever hears it, among all the chemical or other scientific baffle gab, is it not a solemn exercise in silliness*?" To that extent, the ability to withstand cross examination is perhaps secondary to the ability, in the first instance, to effectively communicate what it is the expert wishes to explain before the court.

3.3 Changes to their opinion

The *Ikarian Reefer* principles referenced above envisage and indeed permit experts to change their opinion after considering another point of view. I think it fair to say that experts who change their opinions, for example upon receipt of new information, are respected rather than criticised by the court, provided the reasons for doing so is sound [24]. Equally an expert may change their opinion either as a result of further research and thought or as a result of discussions with other experts, and this fact is uncontroversial. For litigation purposes however, whether such a change of view shows an "*admirable flexibility of thought, or a regrettable inconstancy of mind*" [25] is left to the trial judge to determine.

From a barrister's perspective, a witness who proceeds to change their opinion presents a credibility problem in the case. In *Baulderstone Hornibrook Engineering v. Gordian Runoff (formerly GIO Insurance)* [26] the court observed that the expert witness's many changes in stance suggested a high lack of confidence in his own opinions. From successive reports it was clear that his opinions had changed over time, and indeed continued to change in the witness box, the changes being often quite radical. These changes did not give the court confidence in his opinions and so the weight given to that expert's testimony was limited.

In *Joyce v. Yeomans* [27] it was noted that sometimes an expert witness may refuse to make "*what a more wise witness would make, namely, proper concessions to the viewpoint of the other side*" and judges have on occasion gone further and directed criticism toward a professional witness for failure to acknowledge alternatives. In *Novartis Grimbsy Ltd. v. Cookson* [28] when the Judge was distinctly unimpressed by the expert's unwillingness to reconsider his opinion on causation in the light of the new information brought to his attention and felt compelled to comment on same in his ruling.

All evidence, expert or otherwise, is given to provide a foundation for the court's decision making, not to supplant it or intrude upon the court's function. Put another way: "Judges decide cases, experts do not" [29]. That being said, what is clear from the above is that experts can provide pivotal insights into the forensic world they inhabit and 'lift the curtain' for the Court, showing them the inner workings of the science in order to opine what happened in the case. It is an exercise that is fraught with difficulty and influenced by factors such as communication skills and personality types.

In my experience the witnesses that have impressed me the most are the ones who were willing to concede points and explain their thinking in reply. We are none of us infallible and where an expert presents a scenario with a singular conclusion, the inference they are inviting the court to draw is that their opposite number is fundamentally incorrect. As lawyers, we deal in nuance and probabilities rather than definitive conclusions. Rarely is anything black and white because if it was a foregone conclusion, the case would have settled long before trial. In that context, an expert who can appreciate, acknowledge, and explain the factors that render their case closer to black than white on the spectrum of probabilities, is worth far more than the expert who is adamant they are correct to the exclusion of all other possibilities.

4. CONCLUDING REMARKS

An extensive review undertaken by Ericsson, Prietula and Cokley in the Harvard Business review [30] posits that experts should be viewed in terms of their development, education, training, reasoning, knowledge, and innate talent. In reviewing behavioural data across diverse fields and various areas from sports to music to industry, they concluded "*Consistently and overwhelmingly the evidence showed that experts are always made, not born*".

This author would agree with that statement and add that, in the legal field of forensic evidence, the best experts are those willing to admit when an issue is nuanced, and a view can be reached even if same does not benefit their client. In my role as a legal consultant, I constantly advise clients preparing for trial that their job is not to win the case, in the same way that my job isn't to win a case. Our job is to do our job to the best of our ability and after that, it is a matter for the court.

In my own field of product liability law, I have seen the legal landscape change immeasurably in the past ten years alone. That is not to say there have not always been product liability cases in this jurisdiction but the volume of cases or 'class actions' (though we don't litigate them as such) has grown and with it, the opportunity for judges to consider the law and type of forensic evidence required in order to apportion liability in a case. In the early 2010's cases against Johnson & Johnson began to be brought in respect of their DePuy orthopaedic medical device. Prof. Taylor was arguably one of the most crucial witnesses in those cases and he explained the revolutionary intentions of the product's cobalt and chromium alloy but also how it emitted nano-particles due to ordinary friction and use in patients. These nano-particles caused internal injury and mobility issues for patients but in order to succeed in their claim against the manufacturers of the device, it had to established that the product was dangerously defective, that it failed to function in a mechanically safe way and that this was something Johnson & Johnson were responsible for. While the vast majority of the DePuy cases ended in settlement thereby avoiding the need for litigation, several ran to trial and with it, legal principles were established by the court. I think it fair to say that we have seen more decisions in the area of product liability law in the last ten years, than the last fifty before that and the court in each of those cases could arrive at its conclusions because of expert evidence, including that of Prof. Taylor.

From my perspective it is clear that Prof. Taylor has played a significant role in the area of Irish Product Liability law shaping not just the outcome of a given case but the wider jurisprudence in the area. It is an emerging and nuanced area of law that is only beginning to be applied to medical devices in this jurisdiction and across his forensic career he has explained the issues involved in the proper and safe functioning of medical devices turning his attention more recently to polypropylene pelvic mesh devices. In so doing he has assisted and almost certainly guided judges tasked with forming a view on the scientific evidence in these cases which is no small feat given the complex concepts and scientific nomenclature involved but his skill, to my mind, lies in the ability to distil concepts and convey them in a manner that is accessible.

Dolly Parton once admitted it "costs a lot to look this cheap" and a similar view can be had that it is actually quite hard to make something look easy. Prof. Taylor did that, he did it well and Irish Product Liability Law will benefit from this for years to come.

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THE PROS AND CONS OF FATIGUE LOADING OF BONE

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ABSTRACT

1983 was a big year for the now named Department of Mechanical, Manufacturing, and Biomedical Engineering in Trinity College Dublin. That year saw the arrival of David Taylor to the academic staff which set in motion the establishment of a biomedical engineering research focus, that ultimately acted as the catalyst that initiated huge growth in this area and to the establishment of a dedicated Stream in this discipline. I am one of the fortunate engineers who experienced David Taylor as a teacher (undergraduate), a supervisor (postgraduate), a colleague, and a collaborator. This article will bring you through my time with David and how he has influenced my research, particularly in the area of the fatigue loading of bone, initially focusing of the negative impact it can have on materials utilised to replace bone (i.e. bone cement) before shifting to the beneficial impact of repetitive loading on the bone tissue itself.

1. AN EDUCATION IN FAILURE

I am one of the fortunate engineers who experienced David Taylor as a teacher, a supervisor, a colleague, and a collaborator. My first experience of David as a teacher was in his materials modules in the early years of the engineering program. Despite having >200 students in the lecture theatre David's classes were always very engaging and involved. Like all lecturers, David had to cover the content and the Ashby and Jones books were bibles in that regard, but it was the way that David delivered the content that made his lectures feel like a conversation rather than a lecture. His ability to describe the complex nature and behaviour of common materials was an eye opener and was the first experience within the engineering program to really grasp my full attention and focus my interest. Moreover, I have distinct memories of broken samples being placed on the overhead projector casting a shadow of plastically deformed metals across the wall, many of which were responsible for some catastrophic failure which resulted in significant injury or financial loss. While enthralling to learn of the wonderful world of materials, David's lectures also brought to the fore the reality that materials fail, and the responsibility of the engineer to make sure that nobody gets hurt. A stark realisation to a young engineering student.

The importance of materials in enabling engineering innovation was cemented in David's latter module 'Forensics Materials Engineering'. David was ahead of the curve with his pedagogy, adopting a flipped classroom approach for this module. This allowed the content to be learned on-line in your own time, with a reduced in classroom experience used to discuss case studies of engineering failure. This class was terrifying for two reasons; the first being the constant realisation that things break and the second being that David would single out individual students in the classroom to answer questions on the case study that week. No matter where I sat, he always managed to find me. It is very nearly 20 years since I have taken this module but is one of my most memorable as a student and it is a module that David continues to teach to this day as an Emeritus Professor. Acting as now Director of the Biomedical Engineering program I continually see feedback from the students, where this module is repeatedly highlighted as one of the most educational and rewarding for the students.

Based on my interest in materials, I was fortunate to complete my undergraduate final year project with David. David's approachable and supportive nature, that he demonstrated as a lecturer, also translated to his research supervision. At our weekly meetings, he was engaged, in his relaxed and calm manner, and would always point you in the right direction. Quite remarkable to think of now but David would commonly invite all his final year students to join him after our meetings in Kennedys for a pint. To further demonstrate the support David provides to his students, he even brought me to the Bioengineering in Ireland conference in Jan 2005 in the Fitzpatrick Castle Hotel in Killiney, and it was this experience that ignited my passion for biomedical engineering research. This supportive, collegial, and superior educational environment that David brought to TCD, that was afforded to all students, is a real testament to the academic and person he is.

2. FUN FORENSICS AND THE TOILET NUTS

David's office is never a boring place. With each visit you would come across a new item that had unfortunately broken/fractured and resulted in injury and caused significant damage. These were all part of the forensic failure consultancy work that David performed, in addition to all his academic duties. As a student of David in both my undergraduate and postgraduate years I was afforded the opportunity to work on many of these cases, which were both extremely educational and, in many instances, a lot of fun.

While there were too many to remember, some of my favourites are shown in Figure 1. As an undergraduate, we were involved in a case where a man's golf club fractured while playing, which of course annoyed the man to a great degree. This resulted in a case being taken against the airline/airport that had recently transported his clubs, and it was believed the airline dented his club which subsequently fractured when he went to use it after arriving at his destination. Cue the forensic engineers. The two David's, Peter O'Reilly, and Paul Normoyle attached strain gauges to the club and walked out to the cricket pitch to hit a few balls. I would like to say we managed to hit the black tarp we put up, but…. In a similar fashion, the leg of a 6ft diameter trampoline failed resulting in a few kids injuring themselves. This was before the days of safety nets. Once again, the same characters were out on the cricket pitch having fun. An important attribute of any successful academic is their ability to document and share the work through publication. This is a talent David possesses in abundance as demonstrated by our publication in the International Journal of Fatigue highlighting some of these fun forensic cases [1].

While many of these cases were a lot of fun and highly educational, given that we were coming out of the Celtic Tiger I have to admit the vast majority of cases consisted of broken toilet nuts and related plumbing issues which flooded poorly built apartment complexes. Somewhat less fun.

Figure 1. Some of the many forensic cases we worked on including a fractured golf club, 6ft trampoline, and a hip stem.

3. CEMENTING A BROKEN BONE

After completing my final year project, I remember speaking with David in his office looking for advice on what I should do next. It was then David offered me a postgraduate position in his lab, an offer that changed the course of my career and has enabled us to work together for nearly 20 years.

3.1 Fatigue failure of bone cement

Poly(methyl methacrylate) or PMMA is an acrylic plastic, which is sold under the brand names of Perspex, Lucite, and Plexiglas. This material became one of the earliest biomaterials. It was in 1960 that Charnley saw the material's potential in orthopaedics and was the first to use it in the fixation of a femoral head prosthesis to the femoral bone [2]. Today, bone cement is still the sole material used in the anchoring of a cemented arthroplasty (Fig. 2A). Failure of a cemented prosthesis results in a re-operation or revision surgery. There are many reasons for failure *in vivo* but the number one cause of failure is aseptic loosening of the implant. Although there is some debate as to the causes of aseptic loosening, it has been frequently argued that fatigue failure of the bone cement mantle, leading to implant/cement/tissue interface failure and eventual complete failure of the cement mantle is the primary mechanism of aseptic loosening [3].

Stresses within the cement in the *in vivo* loading situation have been predicted to be low, one third of the fatigue strength of bone cement [4]. Nonetheless failure still occurs. A possible explanation for this may be due to the presence of defects or stress concentrations found within the mantle. As mentioned previously, the stem initially becomes debonded, resulting in an increase in the stresses in the cement [5]. This increase in stress results in multiple fatigue crack formation from stress concentrations in the cement, such as defects and the corners of the stem. As time progresses these cracks propagate and eventually form through-mantle cracks [6] linking the stem/cement/bone interfaces, decreasing the mechanical stability of the mantle. It is clear from the literature that fatigue crack nucleation and propagation from defects or stress concentrations is a major concern regarding the mechanical stability of the bone cement mantle. It is also clear that fatigue crack propagation creates a pathway for wear debris to reach the bone surface initiating osteolysis. Therefore, in order to improve the longevity of cemented artificial replacements it is necessary to understand the role that stress concentrations play in fatigue strength of bone cement.

To address this gap in the literature we produced tensile test specimens (width 16mm, thickness 3.5mm, gauge length 16mm) and introduced various stress concentration features in the form notches and holes with K_t values ranging from 1.44 - 11.04, defined as the maximum stress divided by the nominal gross-section stress [7]. These specimens were hand-mixed, as is common in surgery, and so the resulting specimens had porosity levels in the range 4–15%. Each sample was subjected to fatigue testing on an Instron servohydraulic testing machine (Model 8501). The cyclic stress employed was sinusoidal at a frequency of 3 Hz. The aim was to establish the fatigue strength at a life of 10^5 cycles in order to characterize the effect of stress concentrations in the high-cycle regime. Figure 2B shows stress-life data for some of the samples tested. It is evident that increasing K_t reduced the fatigue strength, but it is also clear that the reduction factor is not as large as K_t. Interestingly, we found that samples which contained notches with low K_t values did not demonstrate a reduced strength and often did not fail from the introduced defect. Failure in these samples, along with that in plain hand mixed samples, were initiated by pores: usually the initiation site contained two or more pores in a cluster. To verify this impact of porosity, we produced pore free samples which demonstrated superior fatigue strength to that of plain hand mixed samples (Fig. 2B). These data demonstrated that stress concentrations are indeed detrimental to the fatigue properties of bone cement, but the presence of porosity made it a little more complicated. To try and better understand this, we turned to the Theory of Critical Distances.

3.2 The Theory of Critical Distances

The Theory of Critical Distances (TCD) is a collection of methods used to predict static and fatigue failure in materials containing stress concentrations. One method is known as the Point Method (PM) and is the method we used in our studies of bone cement. A detailed description of the PM and the TCD in general can be found in a book published by David Taylor [8].

The point method (PM) is applied to the data by considering stress-distance curves drawn for applied loads corresponding to 10^5 cycles to failure, for the various specimens tested. Figure 3C shows the appropriate curves for the hole (ø 2.2mm) and sharp notch (depth 2mm, root radius 0.1mm); also shown is the fatigue strength of plain hand mixed specimens at the same number of cycles to failure. If the PM is applicable, then all three lines should intersect at the same point, corresponding to L/2 and $\Delta\sigma_o$, but clearly they do not. It was hypothesised that this problem arose due to the porosity in the plain specimens; it was reasoned that this was reducing their fatigue strength below the true value for the material. If so, then the true fatigue strength might be found from the intersection of the other two curves on this figure. This intersection point occurs at a stress of 25MPa and at a distance of 0.1mm, so it was assumed that these were the values of $\Delta\sigma_o$ and L/2 respectively. Interestingly, $\Delta\sigma_o$ was very similar to the fatigue strength of pore free samples.

Using these critical parameters, we were able to predict the failure in all notched samples with the exception of the very blunt notches. In the case of these samples, a prediction simply based on reaching the plain-specimen fatigue strength over the net cross-section was found to be accurate, i.e. this notch had no role in reducing fatigue life except insofar as it reduced the load-bearing area. In these samples, porosity was the life limiting factor.

Given the potential detrimental effect of porosity, we next sought to investigate the effect of pores/porosity using the Theory of Critical Distances (TCD). Both hand-mixed (HM) and vacuum-mixed (VM) specimens containing different levels of porosity were fatigue tested to failure and a negative correlation between porosity level and fatigue life was demonstrated, although considerable scatter was present (Fig. 2E). To predict this scatter, we developed failure criterion using the TCD based on pore size and pore proximity (i.e. clustering) that allowed us to predict the high-cycle fatigue strength of individual samples containing specific porosities with good accuracy [9]. Moreover, to predict the scatter, we developed virtual HM and VM specimens using pore size distributions from actual samples (Fig.

2D). Incorporating the effect of pore size and pore clustering predicted using the TCD, a fatigue life prediction could be obtained for the virtual specimens. The virtual data agreed strongly with the experimental findings, predicting the correlation and more significantly the scatter in the experimental results [10]. Using the virtual porosity failure model, it was demonstrated that given a constant porosity the fatigue life can vary by over an order of magnitude in both HM and VM cement (Fig. 2E). This suggests that not only porosity level but pore size distribution is extremely important in controlling the fatigue life of bone cement. Furthermore, given the beneficial effects of porosity it has been proposed that an even distribution of small pores would provide an optimal bone cement mantle. Using our virtual model, it was determined that neither HM nor VM technique was capable of achieving such a distribution indicating a need for a new more reliable approach. The TCD based virtual porosity failure model could prove to be a powerful tool in the design of such a technique.

This body of work revealed the complex role that stress concentrations play in fatigue strength of bone cement and developed novel tools to better understand the failure of this material, which can be used to maximise the potential of this extensively used biomaterial.

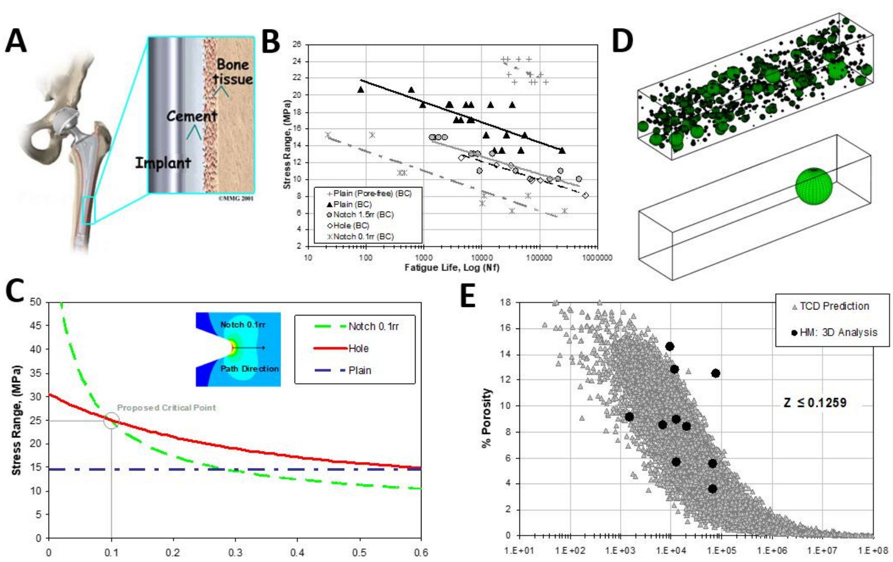

Figure 2. (A) Illustration of a cemented hip replacement. (B) Stress-life data for plain bone cement specimens and specimens containing stress concentrations, rr = root radius. (C) Stress as a function of distance from the defect root, at applied loads corresponding to 10^5 cycles to failure. Also shown is a line representing the fatigue strength of the plain specimens of hand-mixed material. (D) Illustration of 3D virtual specimens; (Top) 8.9% porosity hand-mixed and (Bottom) 1.5% porosity vacuum-mixed (dimensions:

16x3.5x3.5mm). (E) Percentage porosity as a function Nf, for plain hand-mixed 3D virtual specimens. Experimental 3D HM data is also shown for comparison.

4. WHY REPLACE WHEN YOU CAN REGROW

After completing my PhD, it was David again who was pivotal to the direction and success of my career. Inspired by the work David was completing in bone microdamage and subsequent remodelling, I became fascinated by bone as a living tissue, and how it responds to repetitive loading. Fatigue loading, which had been so detrimental in my PhD work, could actually be beneficial to living bone if applied at the correct magnitude and frequency, and this has become the major focus of my research lab over the last decade. Why replace bone with an inert polymer if you have the ability to regrow and regenerate the tissue? To start me on this new phase of my career David introduced me to the late Prof. Christopher Jacobs in Columbia University in the City of New York and luckily vouched for me. It was very likely due to David's recommendation that Chris offered me a job in Cell and Molecular Biomechanics Lab, despite the fact I had never seen a cell before in my life.

Bone is an exquisitely dynamic tissue that is constantly remodelling, repairing, and adapting to meet the demands of the applied physical loads the tissue experiences during daily activity. This is why astronauts who spend long durations in zero gravity need to exercise daily to ensure they do not lose significant bone mass. Given that mechanics is a potent mediator of bone formation, my lab now focuses on better understanding this phenomenon in the hope that we can harness this new knowledge to develop novel therapies and materials to treat devastating bone loss diseases such as osteoporosis and the fractures that ensue.

4.1 Stem/Stromal cell contributions to loading-induced bone formation

Essential to continued bone formation is the differentiation and replenishment of the stem/marrow stromal cell (MSC) population into bone forming osteoblasts. To investigate this process, we utilize ulna/tibia loading to apply a controlled force to the limbs of mice (Fig. 3A), where these mice possess a fluorescently labelled MSC population. Utilizing this model, we could demonstrate that fatigue or cyclic loading significantly enhances bone formation using both dynamic histomorphometry and µCT, but interestingly we also demonstrate that this labelled MSC population is activated in response to loading and is essential for the bone formation process (Fig. 3B) [11, 12]. This new knowledge led to three hypotheses by which this macroscale fatigue loading could generate local signals at the cell level to initiate MSC differentiation and bone formation. Firstly, this macroscale load could generate local mechanical stimuli such as fluid shear which could directly drive MSC differentiation (direct extrinsic biophysical regulation, Fig.3C). Secondly, rather than directly stimulating MSCs, other cell populations in bone such as the osteocyte network may sense this fluid shear and signal via paracrine mechanisms to recruit and differentiate MSCs (indirect biophysical regulation, Fig.3C). Lastly, as the MSC migrates from the marrow niche to the stiff mineralized fibrous surface of bone, this altered substrate may act to influence MSC differentiation (direct intrinsic biophysical regulation, Fig.3C).

Utilising custom bioreactor systems, we were able to demonstrate that the application of cyclic biophysical stimuli alone, such as fluid shear and pressure, can directly drive the osteogenic lineage commitment of MSCs [13, 14]. We next sought to unravel the molecular mechanisms by which these cells can sense these biophysical cues and transduce them into a biochemical bone forming response (a process termed mechanotransduction). This resulted in a series of studies which revealed that MSCs utilize a G-protein coupled receptor called GPR161 to sense fluid shear, which in turn activates a cAMP response in the cells and downstream osteogenesis via the hedgehog pathway (Fig. 3D) [15, 16]. Interestingly, each component of this mechanism was associated with an organelle known as the primary cilium, which is a solitary microtubule based cellular organelle that extends from the surface of the cell into the extracellular space. Ideally positioned to be an extracellular sensor, we demonstrate that this cilium is essential for MSC mechanotransduction and loading-induced bone formation, highlighting the cilium and associated components as novel targets to regrow rather than replace damaged bone [17, 18].

Investigating our hypothesis of indirect biophysical regulation, we have also demonstrated that osteocytes respond to cyclic fluid shear by upregulating and secreting factors that have osteogenic and angiogenic properties, both of which are essential for bone repair [19, 20]. Analysing these factors resulted in the identification of extracellular vesicles (EVs), which are nanometre scale particles released by cells which contain a diverse biological cargo including proteins, nucleic acids and bioactive molecules, and are heavily involved in intercellular communication, regulating tissue development and homeostasis. Isolating these mechanically activated osteocyte derived EVs, we were able to demonstrate that these particles can enhance MSC osteogenesis (Fig. 3E) and angiogenesis and thus represent another novel therapy to enhance bone regeneration.

Lastly, we have also been developing novel biofabrication methods in the form of Melt Electrowriting (MEW) which enables us to manufacture fibrous materials that are on the scale of native mineralized collagen fibres of bone. Utilising MEW we have investigated the impact of local fibre architecture, stiffness, and composition on MSC osteogenesis and have identified a unique substrate to mimic the bone environment [21, 22], which can be used as a scaffold for bone repair. Moreover, combining these substrates with therapies identified above, has enabled us to harness the beneficial impact of fatigue loading and daily activity on the skeleton to better regrow rather than replace damaged bone (Fig. 3F).

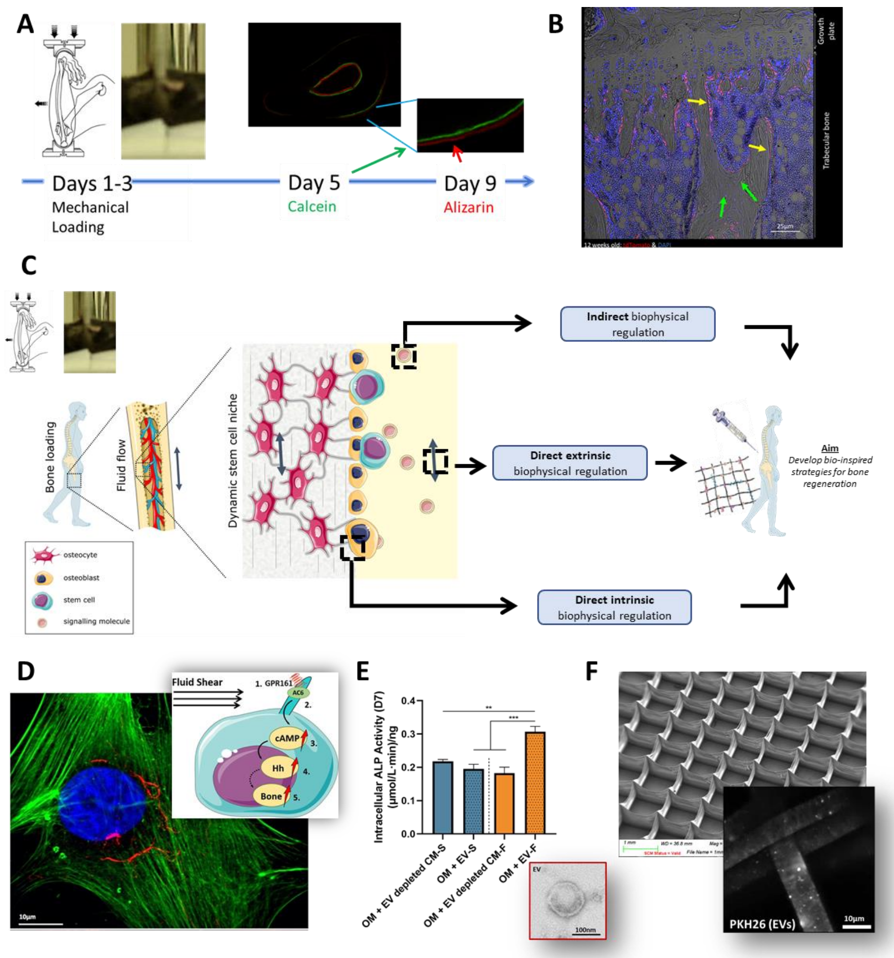

Figure 3. (A) Schematic of murine ulna loading model. (B) Histological image of murine tibia, illustrating the red fluorescently labelled MSC population. (C) Proposed three hypotheses by which MSCs contribute to loading induced bone formation. (D) Immunocytochemistry image of a MSC primary cilium and schematic illustrating identified molecular mechanism of mechanotransduction. (E) EVs released from mechanically simulated osteocytes (OV-F), significantly enhance MSC osteogenesis as indicated by ALP activity. (F) MEW materials functionalised with EVs.

5. CONCLUSIONS

I have written this book chapter in a much more informal manner than I am used to writing but I felt that best reflected my time working with David. I have known David now for 20 years as an educator, a supervisor, a colleague, a collaborator, and as a friend. He is an inspiration in how he is focused on understanding the world around him which he achieves by continuously pushing back the frontiers of fracture mechanics and materials in many often-diverging directions. He has and continues to be a guiding light to me and many others in our own attempt to understand how the world works through our research.

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BIOMECHANICS OF BONE MICRODAMAGE

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ABSTRACT

This contribution is primarily based on my time working with David Taylor, as an undergraduate and postgraduate student on problems involving microcracking and fatigue behaviour of bone tissue. I first got to know David as a 3rd year engineering undergraduate student trying to figure how what I was going to do for my 4th year project. David Taylor had a couple of project proposals that seemed interesting, and I was fortunate to get the opportunity to work on one of these on a study of fatigue cracks in bone. A bright student of David's had recently completed his own PhD- a young man who was to become a leader of the Irish bioengineering community, Clive Lee. He had been monitoring bone modelling using fluorescent chelating agents for his PhD with David and, on a Fulbright scholarship in Harvard, had the idea of using them to label cracks in bone based on problems he encountered in trying to sequentially label damage with basic fuchsin and toluidine blue. My final year project was focussed on testing this hypothesis – working with David and Clive. It worked and more importantly for me, it changed my career direction and led to a HRB funded PhD position working with them both. Everything that followed in my bioengineering career came from this first project with David.

1. MICROCRACKS IN BONE

Many engineers working in orthopaedic research at that time, were focused on the familiar metal/polymer components used in arthroplasty (joint replacement). However, when I started working with David, it was the mechanical properties of bone tissue which was of primary interest. Surprisingly, relatively little was known at that time about the basic behaviour of bone tissue in response to the low-level, cyclical loading that it is so clearly subjected to in everyday life. It was for this reason that we embarked on a project to characterise the nature of fatigue damage in bone and to understand how bone microstructure influenced crack accumulation and growth- as well as attempting to develop new insights into the relationship between microcracks and bone remodelling and their role in stress fractures and fragility fractures associated with osteoporosis.

In Clive and David's previous work, building on theoretical predictions, they had developed a technique to allow microcrack initiation and growth in bone to be monitored during cyclical/fatigue testing [1-3]. This was done using a series of chelating agents – which worked by attaching to the calcium ions lining the crack walls. My PhD research built on this technique and optimised the methodology [4] and utilised the fluorescent properties of the different coloured agents to sequentially monitor crack accumulation and growth. By applying these agents before and at specific intervals during cyclical testing, it was possible to label microcrack development and characterise the process by which they initiate, grow and interact with the bone's microstructure [5, 6]. This research was carried out on bovine bone utilising David's favourite training tool for generations of PhD students, the Instron® machine in the basement of the Parsons Building- ably assisted by the great Peter O'Reilly from the technical staff.

A primary discovery that originated from this work was that microcracks in bone are typically elliptical in shape and grow in a preferential direction, i.e. they are longer in the longitudinal direction compared with transverse. Furthermore, in both directions, growth occurred in three distinct phases, whereby cracks form easily and often, but are then prevented from growing for a considerable period, before ultimately propagating to failure (Fig. 1). It was notable that the microstructural feature of bone, influencing this behaviour was the osteon, formed during the secondary bone remodelling cycle.

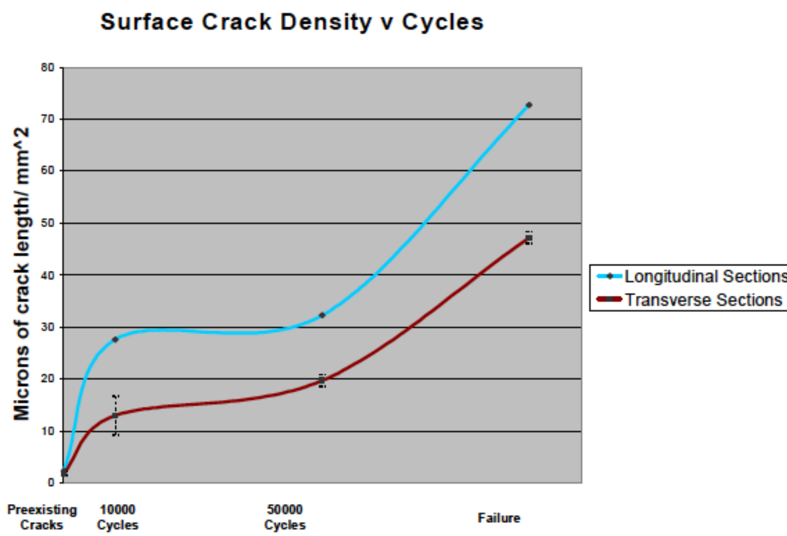

Figure 1. Phases of microcrack growth in bone in longitudinal and transverse directions during cyclical loading [6].

2. MICROCRACK PROPAGATION IN BONE

This was an interesting result and represented a crucial stage in our thinking on this problem. In the world of fracture mechanics, it was well understood that microstructural features in materials, on length scales of microcracks themselves, can dictate how the cracks grow. For metals and ceramics those features typically result from some combination of the material composition, and how it was formed or fabricated – and it is usually possible to understand and predict these processes based on physical and/or chemical principles. However, in the case of bone tissue, these features (osteons) are formed by a complex biological cell-based remodelling process, that was not trivial to understand at a fundamental physiological level, let alone to predict in terms time and space.

This prompted us to study a little more bone biology, and also to use more representative human bone in our experiments – both of which we could do thanks to our links with the Department of Anatomy & Regenerative Medicine in RCSI. The subsequent series of studies were carried out on human rib bones, where we confirmed that microcracks tended to form in 'interstitial' (i.e. relatively older) areas of bone (Fig. 2), and when they began to grow, they did so by taking on an approximately elliptical shape [7]. This was consistent with existing crack growth data published in the literature and confirmed the idea that crack growth occurred relatively easily in the longitudinal direction but is more difficult in the transverse direction. We knew this was a characteristic feature of transversely isotropic materials and was consistent with previous observations from David Burr's group (a leading bone biologist/biomechanist in Indiana, USA) and David's own theoretical predictions [1,8]. Moreover, David's earlier work had also shown that stereological methods could be applied to published crack length data (taken in 2 dimensions) and used to predict 3D crack shape – and sure enough we found that those predictions described the 3D dimensions of the cracks we measured with excellent fidelity. These studies also allowed us to determine that the bone remodelling process, that we were learning more and more about, served to keep these cracks below a critical length, and thus prevent failure - there will be more on critical crack distances/theories in other chapters of this Festschrift.

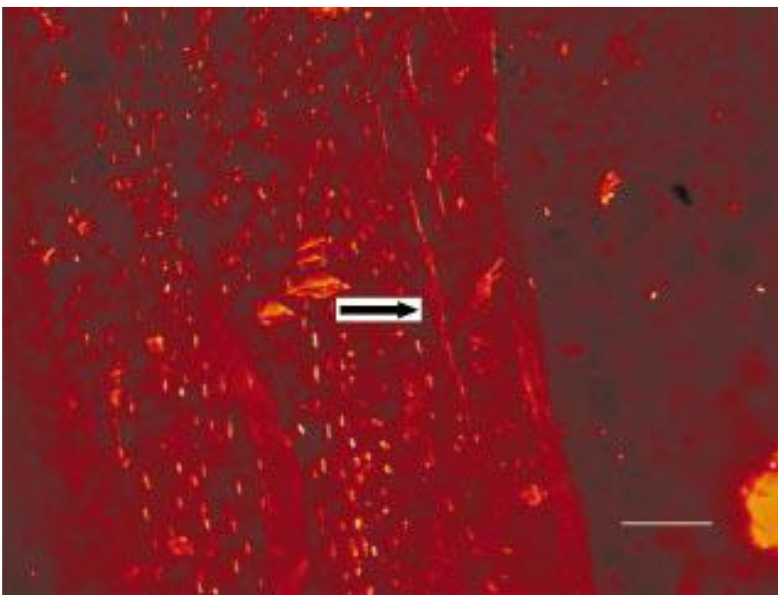

Figure 2. An in-vivo formed microcrack in an interstitial region of human rib bone labelled with xylenol orange viewed with epifluorescence microscopy (scale bar = 50µm) [7].

While the work we had done on the ribs, had a nice element of relevance, in that they were from human tissue, we had no information on the origin and growth of the cracks themselves. So, it was back to the Instron in the Parsons building.

3. FATIGUE PROPERTIES OF BONE

Using young bovine bone, we next sought to determine the fatigue properties and found, again, that our experimental fatigue strength (of 91.6 MPa at 100,000 cycles), compared very favourably with the value of 92.3 MPa predicted by David's model. Not unusually for this kind of testing, a range of several orders of magnitude was noted but this significant level of scatter turned out not to be due to inadequacies in the testing technique, but to the bone material itself. We learned once more about the complex nature of biological materials, which have natural variability in factors such as orientation of collagen/lamellae, porosity and degree of mineralization, among other things which explain the large variation in fatigue life of bone.

These data thus helped to validate the accuracy of David's mathematical model which was able to predict the strength of bovine bone by accounting for the effects of specimen size, temperature and loading frequency [8-10]. They also allowed us to calculate a value for stress intensity (K) for these cracks in the tissue. This was important for a related theoretical model that David was developing to predict crack growth rates, cycles to failure and the rate of decrease of elastic stiffness for bone with a known density of microcracks. Predictions from this model yet again compared favourably with our experimental data. This experimental and theoretical work [11-14], helped us to understand that cracks spend most of their lives in what, for engineering materials is referred to as 'microstructurally short' phase, since they interact significantly with features such as osteon boundaries whose separation is of the order of 100 μm (approximately the size of the cracks themselves).

It was now clear we needed to know more about these secondary osteons. However, this author wanted to complete his PhD and having presented the research to date and helped with organisation of the European Society of Biomechanics meeting chaired by Paddy Prendergast in Dublin in August 2000, submitted his PhD thesis in October of that year. Fortunately, David found some funding and kept me on as a postdoc for a year - so it was back to the Parson's Building basement.

4. OSTEONS AND MICROCRACKS

The work to date suggested that osteons (the primary microstructural unit of cortical bone formed as a consequence of secondary remodelling) play a key role in determining whether cracks propagate to dangerous lengths, or not. Thus, we next characterised more specifically, the relationship between cracks/crack-growth and osteons. We determined that microcracks shorter than 100μm in length, when they encountered an osteon were likely to stop growing, while longer cracks on the order of 150–300μm are likely to continue growing but also to be deflected around the osteon - and then often stop growing soon afterwards which we assumed to be due to increased energy dissipation during deflection. Only microcracks greater than 300μm in length when they encounter osteons were shown to have the potential to grow to critical lengths and cause failure [15]. This research was presented at the 2002 Orthopaedic Research Society in Dallas Texas and was awarded the New Investigator Recognition Award by the ORS – the first prestigious NIRA for Irish research.

We also found that propagating microcracks which grew during at least two stages of the fatigue life curve were found to be significantly longer than those formed at individual periods. Furthermore, we discovered that failure appeared to occur with the propagation of one, or very few, long cracks to critical lengths, rather than by the coalescence of numerous small microcracks. However, an especially interesting observation was that these cracks always penetrated a cement line at some stage on the path to failure [16]. Fig. 3 shows a typical example of two large cracks that were involved in failure of a specimen. It can be seen clearly that, as these cracks grew up to the macro-scale, they penetrated the cement lines of numerous osteons. This was a recurring feature of all the fracture surfaces we studied and has since become a recognisable feature of this kind of failure.

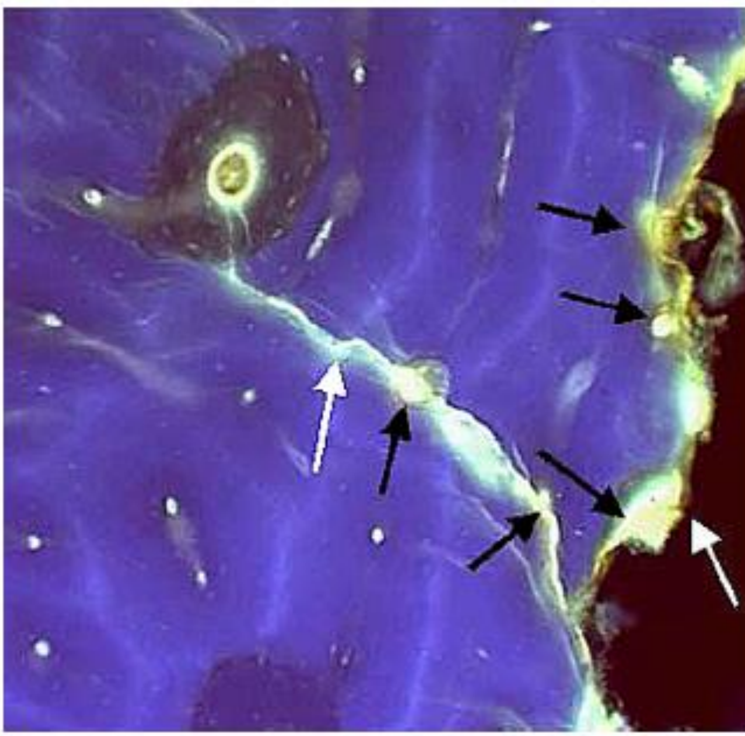

Figure 3. An example of two labelled microcracks (white arrows) which were involved in specimen failure (main fracture surface is on the right). During growth these crack penetrated and grew through the osteonal structure [16].

As is often the case in research, when we came to the end of this work, we had as many questions as we did answers [17]. Chief among them was the idea that while we showed that existing osteons could influence the initiation and growth of new microcracks (from a mechanical perspective) – it might also be the case that an existing microcrack might influence the initiation and development of a new osteon (from a biological perspective). In addition, we now know that microcracks are important to healthy bone biology as they contribute to maintenance and remodelling. Therefore, we had concerns that bone resorption–inhibiting drugs for diseases such as osteoporosis may lead to insufficient bone repair and therefore an increase in microdamage accumulation and ultimately enhanced fracture risk [18]. Indeed, we were eventually proved correct in our prediction with long term clinical bisphosphonate use shown to be linked to atypical femoral fractures.

For me, the story then ended for 2 years as I moved to the US on a Fulbright Scholarship in 2001 to study biomaterials in tissue engineering. However, when I returned to Ireland in 2003, it was to a new adventure and to an Ireland ripe with the excitement of Government funding for research. HEA PRTLI Cycle 3 had led to the establishment of the Trinity Centre for Bioengineering, with funding in place to study more on bone microdamage but increasingly focussed on clinical application and in osteoporosis: the 'Bone for Life' project which introduced partners from NCBES in NUIG and the Veterinary School in UCD as well as the recruitment of a new generation of bright young PhD students- including Oran Kennedy- who will continue the story in his contribution to this Festschrift.

5. CONCLUDING REMARKS

My bioengineering career evolved just as the economy in Ireland began to grow and research funding became widespread. It was the pioneers before this who provided the initial seeds to grow the field into what it has become. They deserve real credit and did stellar work with very little Government or industry research funding. Inter-institutional modern bioengineering as we now know it evolved in Ireland in the early 1980s led by the vision of David Taylor. Building on the interdisciplinary nature of the nascent field, David established the Bioengineering in Ireland Annual Conference – ably supported by his wife Niamh. This meeting has also grown in scale and become a tremendous meeting showcasing the quality of Irish research. David also demonstrated leadership on the international stage – establishing the highly successful *Journal of the Mechanical Behavior of Biomedical Materials* and the International Conference on Mechanics of Biomaterials and Tissues. I was delighted to serve as a founding co-editor of the former and part of the organising committee and a regular speaker at the latter. In 2023, Ireland will be the guest nation at the Orthopaedic Research Society Annual Meeting in Dallas, Texas – a tremendous international recognition of the quality of Irish bioengineering research – all starting from David's vision in the 1980s.

All of us who followed in David's footsteps and who worked under his enthusiastic mentorship were fortunate. The trajectory of my own career from its origins as a confused 3rd year mechanical engineering student owes so much to David's influence. What started out as a BAI bone mechanics project has seen the broader evolution of my research into the area of tissue engineering and regenerative medicine. Now our research is focused on topics as diverse as engineering novel biomaterials, scaffold as models for disease, gene-therapy and drug-delivery therapeutics. We apply these technologies to solve problems in regeneration of cartilage, cardiovascular, ocular, tympanic, neural and even urological tissues. It's been a particular pleasure to see our research used in human patients. However, despite the diversity of tissues I now work with, my favourite tissue is still bone and sometimes I miss the Parsons Building basement…

6. AUTHOR'S NOTE

Special thanks to Dr. Oran Kennedy for helpful discussions and providing the initial framework for this article.

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BONE MICRODAMAGE: SHIFTING OUR SIGHTS TO OSTEOCYTES

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OVERVIEW

My contribution to this collection is based on the time I spent working with David Taylor at undergraduate and postgraduate levels, on bone microdamage and in particular the *biological* response it can generate in the tissue. If that description sounds quite similar to the overview of the previous chapter, by Prof. Fergal O'Brien – that is because it is. As he wrote towards the end of his Chapter, I was the next person to arrive along and pick up the thread of this story, when he moved on to his next position. Just as Fergal's initial work had followed on from that of Prof. Clive Lee, so my first research project followed on from his. Also similarly, just as Fergal enjoyed the double supervision of both Clive and David for his PhD work – so I then enjoyed the supervision, in triplicate, of David, Clive and Fergal for mine. What a wealth of knowledge and experience for a young PhD student to draw on (and what a list of corrections to complete on each thesis chapter!). I first met David as a 2nd year engineering student, during the 'general engineering' stage of the course, when he delivered materials science lectures to our class in the Hamilton Lecture theatre. I remember being fascinated by some of the failure analysis examples he described to us in those classes – particularly those related to orthopaedic implants. This was a large part of the reason I selected the Mechanical Engineering specialty for the latter stages of my degree. During those last two years, like Fergal before me, I was delighted to get the opportunity to work directly with David for my final year undergraduate research project – which was another study of fatigue cracks in bone, but this time specifically as a result of torsional loading. By happy coincidence, certainly from my perspective, one of the senior technical staff in the Department, Mr. Peter O'Reilly, was just beginning his MSc work on a related project at the same time, (which is described above, in his contribution to this Festschrift) – so I was privileged to have yet another wonderful and knowledgeable colleague in my immediate circle at this early stage of my research career. That final year project ultimately turned out very well, and I was quite certain at that stage I wanted to pursue a PhD in the area. However, there was no immediate opportunity for me to do so. Thus I took a brief, and occasionally alarming, detour to the UK, where I spent some time as a graduate mechanical engineer in the foundries and steelworks of Sheffield. Eventually I got the opportunity to return to Dublin on a collaborative project between TCD and RCSI called 'Bone for Life', which was funded as part of the HEA PRTLI Cycle 5 programme. A central part of my specific project was to establish a 'pre-clinical model of osteoporosis'. This would be used to monitor the bone remodelling process and determine whether the fundamental behaviour of microcracks in bone (which David and his group had established in the preceding years) was the same in clinically relevant diseased tissue. We also wanted to understand whether an all-too-common outcome of osteoporosis (i.e. bone fracture) could be understood in terms of microcrack accumulation and propagation. To finish this overview in a similar way to the previous chapter, everything that followed in my bioengineering career came from this first project with Fergal, Clive and David.

1. A PRE-CLINICAL MODEL OF OSTEOPOROSIS

The decision to pursue a PhD is, of course, quite a significant one – particularly if the transition out of academia to an industrial/commercial setting has already been made (as was the case for me). Thus, I had many calls and conversations with my prospective supervisors as I deliberated the move back into academic life to develop that 'preclinical model of osteoporosis'. For me, these calls were usually made on my lunch break, crouching in some corner of a fiery, clanging steelworks in Rotherham, Sheffield or Scunthorpe, struggling to hear over the din of giant steel I-beams being cooled, rolled and straightened nearby. I remember my occasional attempts to impress the hardened Yorkshire machine operators, with my knowledge of how Castigliano's theorem might apply to the structures they were producing, never quite hit their mark. This was despite the assurances I had been given during my undergraduate solid mechanics lectures in the Parsons building that this information would undoubtedly come in useful someday. In contrast, at the other end of the line on those calls with David, Clive and Fergal in the peaceful academic surroundings of TCD, RCSI and MIT, respectively seemed very appealing indeed. In my mind, visions of grand ivory towers and peaceful quadrangles and libraries were beginning to form. There, I would sit for endless quiet hours, thinking and planning experiments on bone biomechanics to figure out new ways to accurately determine fracture risk. This, however, was not exactly how things turned out.

Once the decision was made, and I had returned to Dublin to begin my PhD, one of my first tasks was to learn what exactly a 'pre-clinical model of osteoporosis' actually was - and how I might go about establishing one. It was around this time that the vision of my future in libraries, labs and lecture-halls began to quickly evaporate. Instead, I became a regular visitor to the School of Veterinary Science in UCD (with our collaborator Prof. Sue Rackard), sheep marts in county Wicklow, and a farm in Co. Kildare called Lyons Estate. Before long, I (and the rest of the Bone for Life team) became stewards of a large group of approximately 70 female sheep - the correct term for which is 'ewe' – and the correct pronunciation of which, as I was reliably (and repeatedly) informed, is '*Yo*'. These animals were the foundation of our pre-clinical large animal model for osteoporosis. The reason being that with the removal of estrogen (through a surgical procedure called ovariectomy [OVX]), the sheep skeleton, behaves very similarly to the human post-menopausal one, specifically in terms of its bone remodelling cycle. This explanation, and comparison, was one I learned to make very carefully as I began presenting my work at research meetings. This is because, after one of my first ever talks, I received a fairly pointed query from an audience member about my rather loose and careless description of this similarity between the human, and the ovine, in terms of their responses to estrogen loss. While all of this was not quite the first year of graduate study that I had been expecting, it was a fantastic experience from which many friendships, collaborations, and amusing stories, grew.

It is a fairly well-known fact that there are about 206 bones in the human skeleton. One of next lessons I learned on my project, this time in comparative anatomy, was that there a few more in the sheep skeleton – a total of 215 to be precise. Once again, the practicalities of the project swiftly took over, as I realised we needed to collect, label and store each and every one of these, from all 70 study participants, in a freezer-filled basement in RCSI - where some of them remain to this day. Then the process of preparation, testing and analysis began. As the first data-sets emerged, we found that with the removal of estrogen *via* OVX intracortical bone remodelling activity in this model was dramatically increased, just as it is in humans (Fig. 1). An equally dramatic change occurred in local bone material properties along with a concomitant increase in tissue porosity.

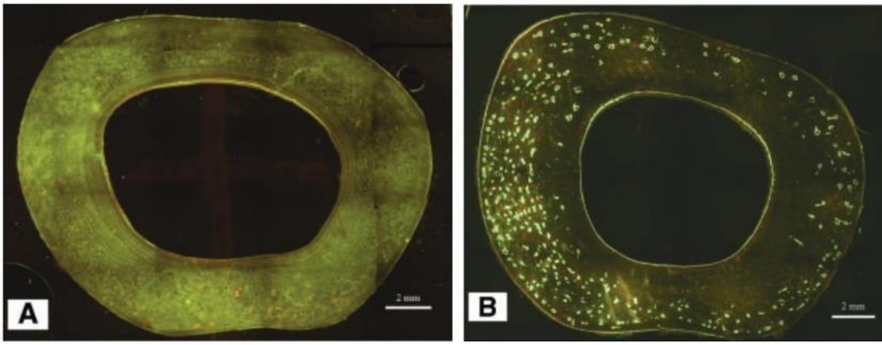

Figure 1. Composite histological images of ovine cortical bone from animals that were given fluorochrome bone-labelling agents *in vivo*, to track bone remodelling activity under (A) Control or (B) Ovariectomised (OVX; i.e. lacking estrogen) conditions. Each point of coloured light in the tissue represents a site of bone remodelling (scale bar = 2mm) [1].

These changes translated into a reduction in stiffness and yield strength although with no change in the post-yield parameters of compressive strength and work to fracture after 12 months. Our findings supported the view that increased bone remodelling was an important consideration in the assessment of bone material and mechanical properties. It also highlighted the need to examine a number of different parameters of bone *quality*, as opposed to just bone quantity (which was essentially the clinical gold standard of the day, as measured by DEXA scanning). Moreover, it suggested to us that improved understanding of this aspect of bone biomechanics/mechanobiology could lead to the development of new treatments and therapies. And in some, albeit indirect ways, as I hope to show, it did.

2. FATIGUE CRACKS IN OSTEOPOROTIC BONE

In order to determine the microcrack behaviour in these tissues, we set about generating them using those time-honoured methods of fatigue-testing using the Instron machine in the basement of the Parsons building again. The data we generated are represented in Fig. 2 with best fit curves drawn according to the Weibull equation:

$$\text{Probability}(x) = 1-\exp(-(x/\lambda)^k) \text{ (where } \lambda \text{ and } k \text{ are constants} > 0) \quad (1)$$

They suggested to us that the microstructural changes seen in our initial studies caused an approximately 7% reduction in fatigue life for OVX bone. This was not quite as big an effect, as the changes in porosity might have suggested. However, the follow-up histological studies were particularly enlightening on this point, as they went some way towards explaining why this might be the case.

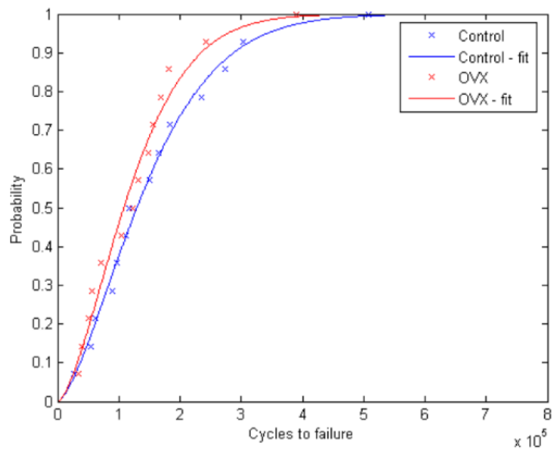

Figure 2. Weibull best-fit probability curves of predicted failure of control and OVX bone as a function of cycle number from bending fatigue tests [2].

The increased porosity had the effect of creating more crack initiation sites, *via* stress concentrations. The more recently formed, newer, osteons also had the effect of 'attracting' more propagating cracks towards them. However, they also displayed a compensatory effect, based on their lower mineralisation levels, whereby they would arrest crack growth more readily than older osteons. Examples of this phenomenon, as well as a simple illustration of this hypothetical model, are shown in Fig. 3.

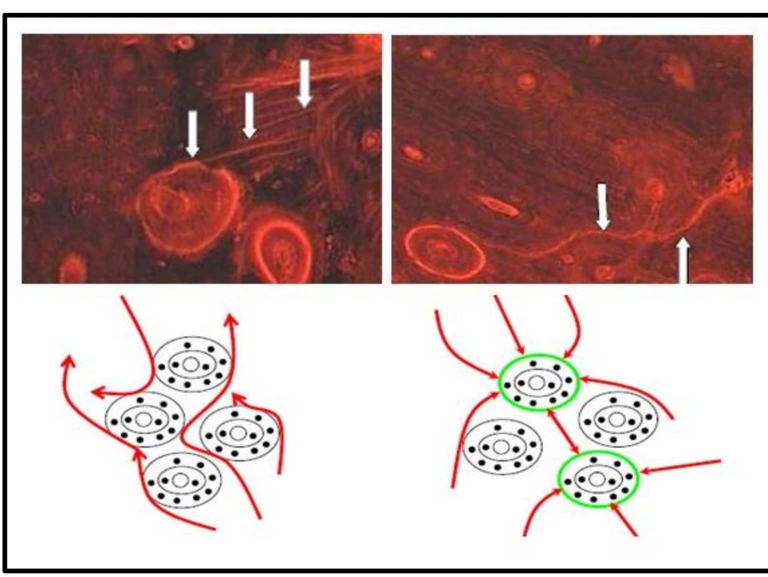

Figure 3. Representative examples of undecalcified cortical bone samples, stained for microcracks (white arrows), and their interactions with (labelled/unlabelled) osteons are viewed using epifluorescence microscopy (upper panels [3]). Illustration of hypothetical model of this relationship is shown in the lower panels.

3. MICROCRACKS AND OSTEOCYTES

From here, our work began to take quite a different (and for me, career altering) turn. Up to this point, we had focused almost exclusively on the mechanical interaction of fatigue-induced microcracks with pre-existing osteons. Furthermore, we worked on the premise that the former (microcracks) were ‘attracted’ to the latter (osteons), during our laboratory-based fatigue testing studies. However, from some of those long thoroughly enjoyable conversions over coffee with David, the next evolution of this idea emerged. We reasoned that in real life, the situation might also work the other way around. In other words, that bone remodelling units could actually be directed to, or attracted by, naturally occurring microcracks to facilitate their repair. If this was so, what could be the source of such a signal from a microcrack (which is essentially a small discontinuity in a largely inorganic matrix) to compel a multi-cellular osteoclast driven entity to find and remove it? The answer to this can be seen lurking in the background of Fig. 4 (which is an image from our sheep study, that nicely captures an osteon mid-formation) and is, in case you haven’t guessed already, the osteocyte.

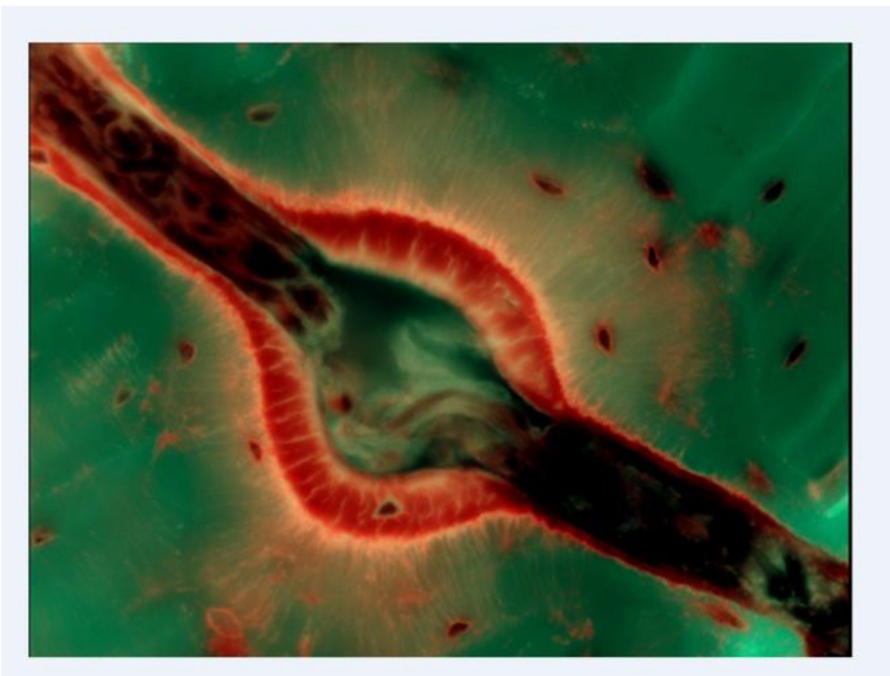

Figure 4. Histological cross-sectional image of an osteon, mid-formation, labelled *in vivo* with xylenol orange, Volkmann’s canals are also visible emerging from either side of the central Haversian system [4].

However, one of the very many things my PhD external examiner (and future Post-Doctoral fellowship mentor) Prof. Mitchell Schaffler said to me during my *viva voce* was "…ideas are easy, data is hard". Thus, we set about writing a proposal to define this hypothesis and generate the data to test it. This involved an application for a Fulbright Fellowship to carry out this work, with Prof. Schaffler, in his lab at the Department of Biomedical Engineering, in the City College of New York. That application was successful, and I moved to New York to begin work on a different kind of pre-clinical model. This time it was a murine one in which microcracks could readily be introduced using an *in vivo* mechanical loading system. Then the biological responses they induce (and their source) could be determined. This work resulted in a crucial evolution in our understanding of the problem. In the world of bone biology, it had been generally thought, for a long time, that osteocytes were little more than placeholders in the tissue. They were thought to make few contributions to tissue homeostasis compared with the prodigious creation/removal of bone attributed to osteoblast/osteoclasts, respectively. Our data showed that if an osteocyte were to be damaged by a propagating microcrack, which a glance at Fig. 3 above (or any of the histological images in the previous chapter) would suggest must be the case – then they would produce a molecule called Receptor Activator of NF-kappaB Ligand (RANK-L). This molecule, among some others that osteocytes produce under these conditions, is a potent activator of osteoclasts, which direct the bone remodelling units that can remove cracks and create osteons. This was an entirely new function which we were ascribing to osteocytes, but it was one which was also beginning to emerge in other quarters. That same year, two separate research groups published ground-breaking papers in the same edition of the *Nature Medicine* Journal showing conclusively, using genetic mouse models, that osteocytes were not only *a* source, but *the* primary source of the osteoclast controlling factor RANKL in the skeleton [5, 6]. While our work on the specific microcrack-related version of this relationship did not make it into the pages of *Nature Medicine*, it was published in *Bone.* Also in another mild example of history repetition, like Fergal's early work on this topic it was also awarded the New Investigator Recognition Award (NIRA) at the 2011 Orthopaedic Research Society meeting in Long Beach, CA.

This directed our work still further into the world of bone cell and molecular biology. What was the precise result of a microcrack interacting with an osteocyte, to initiate this signalling process? David, along with some of the students that followed me on this work back in TCD, were focussed on the potential for cracks to cross, and sever, the cell processes (that work is discussed elsewhere in this Festschrift.). Whereas we focussed on damage at the cell body – specifically damage that results in cell death. As we were continually reminded, concepts that might sound simple to an engineer (like 'cell death') can have wide and various definitions in the world of biology. For example, cell death can occur *via* necrosis, apoptosis, necroptosis, pyroptosis, autophagy or entosis. Ultimately by using specific inhibitors of the process, we discovered that apoptosis was a required stage through which osteocytes must pass, in order or them to illicit an osteoclast-mediated remodelling response in cortical bone [7].

Though our work was increasingly focussed on biological aspects of this problem, we never quite stopped thinking about microcracks from a mechanical perspective. In various side projects we revisited and continued the work that I had started in my PhD with David. For example, our study of whether common treatments for osteoporosis, such as the bisphosphonates, can affect fracture toughness. Bisphosphonates are excellent drugs for preventing the bone loss by directly and potently targeting osteoclasts. However, while preventing their *over*-activity (as in the case of post-menopausal osteoporosis) is a good thing, preventing their regular activity is not – and can lead to microcrack accumulation. We had been suggesting this might be the case for some time when reports began to emerge of unusual fractures that occurred, with very low force, in osteoporosis patients on long-term bisphosphonate treatment. Thankfully, it turned out that this problem of Atypical Femoral Fractures (AFFs), as they were to become known, was not one that would affect all long-term bisphosphonate users, but rather quite a small (yet significant) sub-group.

Once again, we learned about the complex nature of biological materials, which invariably seem to have very specific highly evolved, responses to mechanical stimulus like microcracks. For me, this process also highlighted the way in which (relatively) simple questions, such as ‘how do microcracks behave in bone?’, can lead down a wonderfully rich and tangled path of research questions and answers, which often end up having applications that were completely unforeseen at the outset. To close out this reflection, and to pick up on the statement from Section 1 that David’s work has ultimately contributed ‘…to new treatments and therapies’, it was quite gratifying to note over the last 10 years, that those bisphosphonate drugs, which were the gold standard treatment for osteoporosis for so long, have slowly been giving way to a new class of drug. One of these is called Denosumab, which is a human monoclonal anti-body treatment, specifically designed to target RANKL: the very same factor that we found in osteocytes damaged by microcracks.

4. CONCLUDING REMARKS

For me, this story has continued to underpin many of my research interests right up to the present day. In 2012 I established my research group as a new faculty member in the Department of Orthopaedic Surgery in New York University. I had been due to return home around that time, as per the return phase of my Fulbright fellowship – but due to the ongoing economic crisis at that time, my sponsors graciously allow me to extend my stay. The first proposal that was funded was based on the idea that microdamage in bone is important in yet another clinically relevant application. This time in the case of acute joint injuries such as Anterior Cruciate Ligament (ACL) damage of the knee. These injuries often result in subchondral 'bone bruises' around the joint which can be seen by Magnetic Resonance Imaging (MRI). These bruises, it turns out, are yet another manifestation of bone microdamage, and they may turn out to be targets of new treatments for joint injury and disease. When I returned to Ireland in 2017, this idea was taking further shape and gaining momentum and I was lucky enough to have different aspects of it funded by Science Foundation Ireland, under the Career Development Award (CDA) scheme and also by the EU Horizon 2020 programme under the Marie Curie Sklodowska Award (MCSA) programme.

I have been immensely fortunate to have had a succession of great mentors and colleagues who have helped me progress through my career to this point. As with so many of the other contributors to this Festshcrift, it all began thanks to David's vision, enthusiasm, and dedication to his students. The project that David devised for my undergraduate research project on torsional fatigue cracking in chicken bones was the steppingstone that allowed me to earn my PhD, to travel to the US for a postdoctoral fellowship, to establish my own lab there, and then ultimately to return to Ireland for the academic position I now have in RCSI. I am so very grateful to David for his role in starting me on this path which has been, and hopefully will continue to be, an extremely fulfilling one – and, even if it is not always the tranquil 'ivory tower' version of academic life that I had once envisaged, it is a significant improvement on those steelworks in Sheffield.

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THE SECOND MOST COMMON BIOLOGICAL MATERIAL IN THE WORLD – A BRIEF HISTORY OF INSECT CUTICLE RESEARCH

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"[The] wagon-spokes [are] made of long spinners' legs, the cover of the wings of grasshoppers, [...] her whip of cricket's bone..."

Mercutio describes details of Queen Mab's miniature fairy wagon,
Shakespeare's Romeo and Juliet, 1599

ABSTRACT

Insect cuticle is one of the most common and versatile biological composite materials in the world. Its biomechanical properties haven been studied by zoologists, engineers, and materials scientists for decades, however with relatively little interaction between the disciplines. David Taylor and I have had the great opportunity to start an interdisciplinary project, where we combined state-of-the-art engineering techniques with zoology to analyse fundamental questions on the biomechanics of cuticle. Together with a growing team of highly motivated and interested students, we were the first to publish experimental values on the fracture toughness of cuticle, the first to show data on fatigue properties of cuticle and the first to demonstrate targeted cuticle deposition during healing. This paper summarises the start of a still ongoing exciting interdisciplinary scientific journey.

1. HOW DO INSECT LEGS BREAK?

When I first joined David's group in summer 2010, I had just finished my PhD at the Department of Zoology in Cambridge, where I had worked on understanding the secrets of insect adhesion. Funded by an IRCSET postdoctoral fellowship, David and I were very keen on starting on our work together on the biomechanics of insect cuticle.

Our first goal was to somehow find a reliable method to measure the fundamental biomechanical properties of insect cuticle. We had found a few "classic" papers from the 1940's, 1960's and 1970's describing simple experiments to measure strength and stiffness of locust tibiae [1]–[3]. To our surprise, since then, not much biomechanics research had happened on "the second most common biological material in the world" (a phrase which became a signature introductory paragraph in many of our manuscripts). Now about half a century later, David and I were wondering whether combining "proper" engineering and some zoology with advances in measurement techniques might lead us to new insights on insect cuticle. In particular, we found that there was almost no reliable data on the fracture toughness of cuticle, a material characteristic in which David was obviously very much interested in. During our initial literature survey, we traced the very limited fracture toughness data through various papers through several decades. Our search however ended in a paper, citing the single value as "personal communication". We wanted to change this, so in the late summer of 2010 David spent quite some time explaining to me the fundamentals of experimental fracture mechanics of biological materials – and many of them using hand drawn sketches on napkins at the TCD buttery.

I then started to break insect legs in the basement of the Engineering Department – which looking back sounds quite like a "mobster academia" approach. I still remember the first time I came to David's office to show him the results of my first cantilever bending tests on the hind leg tibiae of *Schistocerca gregaria* locusts. Having spent several long days in the lab trying out various kinds of fixation techniques and experimental parameters, I felt that all my efforts had been in vain. All my leg samples had broken at various places and there was no way I could make sense of the stress-strain curves. I was quite frustrated until I noticed David's excitement about the force-deflection curves. We spent hours looking at countless SEM images showing cuticle cracks of various types and sizes. To this day I am amazed about what an expert like David can see in and learn from "just a broken insect leg".

We then refined our experiments and kept looking for the "perfect" experimental setup to measure fracture toughness in insect cuticle. Peter O'Reilly, Clodagh Dooley and Mick Reilly were a great support during this time and probably wondered more than once what David and I were up to with our requests to make sample holders for the Zwicks smaller and smaller, sputter coat another twenty legs for SEM, and measure tiny forces with machines usually used to break steel and ceramics.

After a few weeks we got our next data set on the locust tibia properties. When we then compared our results with the few data points available in the "classic literature" on insect cuticle, we were puzzled by what we found. Initially, we had expected the Young's modulus of cuticle to be in the range of about 8 to 9 GPa [4]. However, our results showed that the stiffness of our locust legs was more in the range of 3 to 4 GPa. Initially, we believed that something must have been systematically wrong with our experiments. However, taking a closer look at the original paper, we noticed that in the 1960s, Jensen and Weisfogh had measured their locust legs after the dental cement used to embed the samples had dried for one hour. This must have had led to significant desiccation of their cuticle samples. In our experiments 50 years later, we however were using rapid curing PMMA cement, which allowed us to perform measurements within minutes after the leg had been removed – a small yet meaningful experimental difference. We expanded our data set to include legs desiccated for one hour and were finally able to reproduce the results from Jensen and Weisfogh. This gave us the final confidence to pursue further measurements and start investigating the fracture mechanics of the locust hind leg in more detail.

We then started inducing small notches into the tibia, measure the respective maximum bending strength to calculate the cuticle's fracture toughness (see Fig. 1A). Our results show that the fracture toughness of cuticle in locust hind legs is 4.12 MPa $m^{1/2}$ and decreases with desiccation of the cuticle. This value itself was not particularly exciting for a biological material, however the combination of the cuticle's high fracture toughness with a relatively low stiffness results in an extraordinarily high work of fracture of 5.56 kJ m^{-2}. This value is amongst the highest of any biological material, placing cuticle in the range of antler and bone (see Fig. 1B). Looking at the biological relevance of our results, this outstanding work of fracture gives the insect leg an exceptional ability to tolerate defects [5].

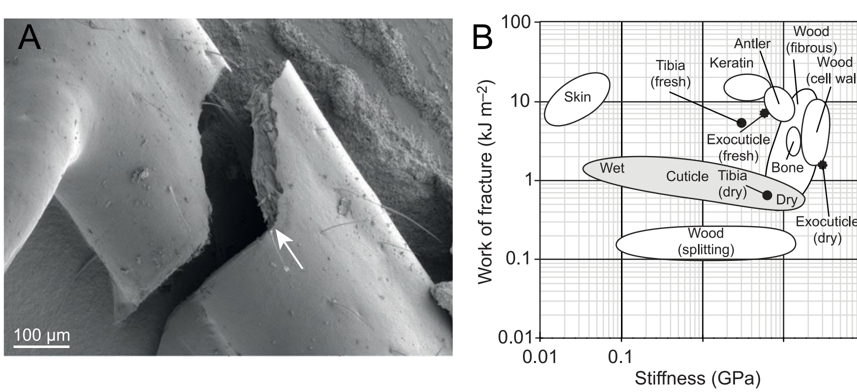

Figure 1. A) Scanning electron microscopy image of *S. gregaria* tibia showing an initial straight notch induced using a scalpel (left towards arrow) and the crack resulting from fracture of the tibia through cantilever bending. These measurements were used to calculate the fracture toughness of the tibia cuticle. B) Work of fracture and stiffness of selected biological materials with our own results for fresh and dry locust tibia (solid circles). Our results showed that tibia cuticle has one of the highest fracture toughness of all biological materials. Figure adapted from [5].

An analytical tool that turned out to be exceptionally useful for our projects was a microCT located at the Department's basement. In contrast to the "classic" zoological studies, where samples had to be histologically embedded, cut and analysed slice by slice, this machine allowed us to quantify the 3D morphological parameters of complex exoskeletal structures destruction free at very high accuracy.

The highly detailed morphological data we acquired from our scans, together with comprehensive data on the mechanical properties of the tibia quickly led to our next exoskeleton paper [6]. In this paper David and I followed an almost entirely theoretical approach and addressed the strength and mechanical failure in exoskeletons. When limbs of arthropods are modelled as simple tubes one can model different failure modes and their interaction. We tested the hypothesis that evolutionary adaptation tends towards the value of radius and thickness which gives the highest strength (i.e. load-carrying capacity) for a given weight. We also looked at other arthropods and found that the crab merus experiences similar levels of bending and compression *in vivo* and that its radius/thickness value represents an ideal compromise to resist these two types of loading. The locust tibia, however, is loaded almost exclusively in bending and was found to be optimized for this loading mode.

2. WHY DON'T WINGS BREAK?

Up to then, our studies had primarily focussed on the locust tibia. This interest was primarily driven by the tibia's almost tube-like geometry and the possibility to perform simple cantilever bending tests. However, as we had discovered the very high fracture toughness of the tibia, we were wondering whether other exoskeletal body parts might show an even higher resistance to crack propagation. To investigate this idea, we started looking at the hind wings of locusts [7]. Locusts are the "marathon flyers" amongst the insects, capable of migrating for long distances through deserts and even across oceans. During the typical lifetime of a locusts, its wings are therefore subject to millions of cyclic loadings. As the micrometre thin wing membrane has a very limited healing capacity, any defects in the wing may reduce the insect's flight performance.

To analyse the biomechanical properties of the wing, we performed quite simple tensile tests on sections of the hind wing. The experiment itself was not particularly complex, however it took us quite some time to figure out the best way to cut and fix a section of the wing in a suitable sample holder. Ultimately, a small frame made from aluminium foil and superglue did the trick – both essential tools in any biomechanics lab. We then induced a small notch in the wing membrane and measured the force required to elongate the crack. To our surprise, our results show that, compared to other body parts, the hind wing membrane of the locust itself was not exceptionally tough. However, when we took a closer look at the way the crack moved through the hind wing, we noticed that the cross veins acted as crack barriers, delaying and deflecting the propagation of the crack through the membrane. The presence of cross veins thus increased the fracture toughness of the hind wings by approximately 50%, which is quite an impressive effect. We then asked ourselves: if the cross veins have such a large impact on the wing's fracture toughness, why not have more cross veins? Is there a biomechanically "ideal pattern" for cross vein distribution?

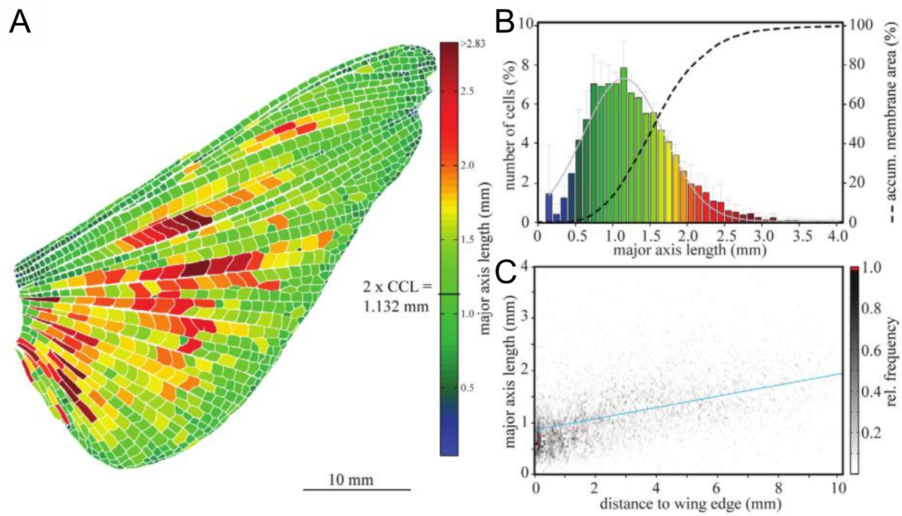

Figure 2. Size and distribution of wing cells in *S. gregaria* hind wings. A) Typical structure of a locust hind wing, showing the distribution of the wing cell size within the wing. Cells with smaller major axis lengths are mostly arranged around the perimeter of the wing (CCL: critical crack length). B) Mean frequency of wing cell sizes from six hind wings. Most cells within the hind wings are around the mean major axis length of 1.103 mm, which corresponds to the CCL of the membrane. (c) 2D-Histogram showing the relative frequency of cell size and their distance to the wing edge. With increasing distance to the wing edge, the size of the cells increases. Figure adapted from [7].

Using fracture mechanics, we then showed that the morphological spacing of most wing veins matches the critical crack length of the material (see Fig. 2). A crack within a single wing "cell" thus cannot reach a critical crack length before being stopped by the next cross vein. Larger cells would decrease the wing weight, however, it would also increase the chance of a crack propagating through the wing. On the other hand, smaller cells (with more cross veins and a higher overall weight) would be "unnecessary", as they would stop the crack sooner than biomechanically required. We also found that the size of the wing cells increases towards the centre of the wing, where cracks due to wear and tear are less likely. This finding directly demonstrates how the biomechanical properties, and the morphology of locust wings are functionally correlated, providing a mechanically 'optimal' solution with high toughness and low weight. Several years later we continued and expanded this study together with Jonas Schmidt [8] and were able to show that David's Theory of Critical Distances could accurately predict the passage of a crack through a wing vein.

3. DAMAGE AND REPAIR

In 2012 Eoin Parlé joined our "cuticle team" at David's group. Inspired by the tensile tests we performed on the hind wings, we now started to systematically investigate the fatigue properties of insect cuticle, an almost untapped scientific field [9]. Using force-controlled cyclic loading, we determined the number of cycles to failure for hind legs and hind wings of locusts as a function of the applied cyclic stress (see Figure 3). Our results show that, although both body parts are made from cuticle, the wings and tibiae behaved very differently. Wing samples showed a large fatigue range, failing after 100,000 cycles when we applied 46% of the ultimate tensile strength (UTS). Legs, in contrast, were able to sustain a stress of 76% of the UTS for the same number of cycles to failure. Our results also showed that the final failure of the tibiae occurred via one of two different failure modes – crack propagation in tension or buckling in compression – indicating that the tibia of the locusts is evolutionary optimized to resist both failure modes equally.

Building up on our new insights into how cuticle can fail under cyclic loading conditions, we then shifted our focus onto more "dynamic" properties of cuticle exoskeletons. We had noticed that basically nothing was known about the healing or repair mechanisms of insect cuticle or the biomechanics of repaired cuticle. If the exoskeleton of an insect is injured, can it repair in a manner which is mechanically strong and viable? As part of his PhD thesis, Eoin started to analyse fundamental principles of injury repair processes in locust exoskeletons. Eoin first spent a considerable time to find a way to create controlled incisions into the tibiae of locusts without the locusts just "throwing off their legs". Having mastered this experimental challenge, Eoin was then able to show that after an incision, a healing process occurred which almost doubled the mechanical strength of the locust tibial cuticle. A particularly interesting aspect was that the results clearly showed that this repair process occurred by targeted cuticle deposition and was directly stimulated by the presence of the injury. The deposition rate of endocuticle inside the tibia increased fourfold compared with uninjured controls, but only on the dorsal side, where the incision was placed [10][11].

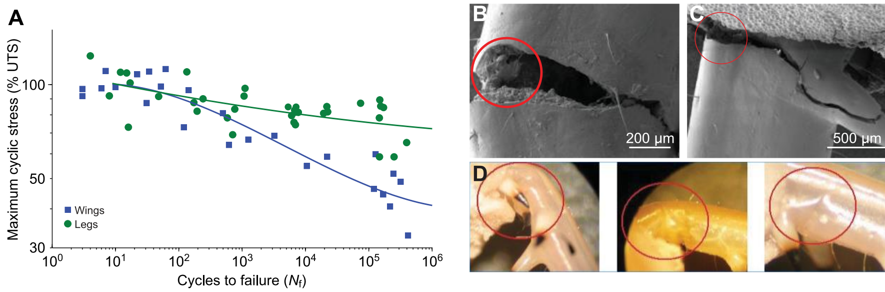

Figure 3. A) Results of fatigue tests on locust hind wings and hind leg tibiae. Cyclic loading tests demonstrated that fatigue failure occurs in both legs and wings, with the number of cycles to failure increasing as the cyclic stress was reduced. These results show that different body parts can have notably different behavior when subject to cyclic loading B-D) SEM and light microscopy revealed different modes of failure during cantilever fatigue tests. All figures adapted from Dirks *et al*. (2013).

4. YOUNG AND OLD INSECTS

As this study showed that cuticle is a notably more "dynamic" material than previously thought, Eoin and David then continued to study changes in the exoskeleton of locusts. So far, we had only been looking at fully mature insects and used these as our reference animals. However, we were not sure if and how the biomechanical properties of cuticle might change during the lifetime of an insect. To investigate this question. Eoin and David performed a very comprehensive long-term study, analysing the properties of cuticle for two months following the final moult [12]. Cantilever bending tests revealed that Young's modulus and failure stress increased rapidly during the first few weeks of growth, but remained almost constant at a high level during the mature phase. During the ageing of the exoskeleton, the failure mode also changed, from local buckling of the tubular leg during the growth phase to failure at the material's ultimate strength in the mature phase. Over time, the ratio of radius/thickness of the leg decreased, passing through the estimated optimal value which would confer the best strength/weight ratio. This study was the first ever biomechanical study to systematically track changes in arthropod cuticle over a large part of adult life of the animal. It revealed some unexpected and complex changes which, as most exciting scientific studies do, triggered additional new questions on how arthropods regulate their load-bearing skeletal parts during aging.

The effect of ageing on the mechanical properties of cuticle was a very promising and interesting new field and thus became the focus of Maeve O'Neill's PhD work, when she joined the cuticle team. Maeve combined several aspects of our earlier studies and investigated the possible effects of ageing on repair of cuticle. Together with Diego Delandro they discovered that younger insects were significantly better at repairing injuries than older insects, displaying no significant decreases in failure strength, stiffness or bending moment to failure after 3 weeks of repair. Older locusts, in contrast, were only capable of repairing up to 70% of their original strength. Older and younger insects both carried out targeted deposition to repair injuries, which confirmed and expanded our previous study on cuticle repair. The team also discovered that the cuticle of older insects is more susceptible to crack growth due to a large decrease in fracture toughness with age.

Maeve then continued to investigate several of the open questions on how cuticle reacts to cyclic loading [13]. To understand the possible effect of microdamage on cuticle, Maeve and David applied cyclic bending loads to the hind tibiae. Their results showed a significant decrease in the cuticle's Young's modulus with an increasing number of loading cycles. These results indicate that during the mechanical loading, microdamage within the cuticle could have been induced. When the tibiae however were allowed to heal, the decrease in stiffness disappeared, indicating that the microdamage could have been repaired. This study was the first ever indicating that insects could be able to repair mechanically induced microdamage.

5. CONCLUSION

David and I first started our joint research on insect cuticle in summer 2012. Within the following ten years and with the help of many talented and highly motivated researchers from both engineering and biology we were able to answer (and raise) several fundamental questions about the biomechanics of this highly fascinating material. New experimental techniques and analytical approaches allowed us to gather exciting new data and intriguing insights. However, more than any exciting or elaborate experimental setup, David's outstanding ability to guide, educate and motivate students and young researchers has been the key factor on this exciting journey – which will certainly keep us busy for many more years to come.

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PROF. DAVID TAYLOR – A CRITICAL DISTANCE TRAVELLED FOR BIOENGINEERING

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ABSTRACT

Professor David Taylor has had an extraordinary and widely expansive career in materials and biomedical engineering. His passion and enthusiasm for understanding how and why materials fail is truly inspirational. David is now considered one of the "godfathers" of Bioengineering activity in Ireland in modern times – as Prof. Clive Lee so nicely outlined in the first chapter of this Festschrift. His dedication and contributions to the field have been immense and wide ranging, from the founding of the Bioengineering Research Centre to the establishment of the Bioengineering Design Forum and our annual national conference Bioengineering in Ireland, to being an expert witness for investigations into the failure of hip prosthesis and surgical meshes as well as being the inaugural editor in chief of the Journal of the Mechanical Behavior of Biomedical Materials. His knowledge, depth of understanding and passion has had a major impact on a vast number of students, researchers and academics in Ireland and abroad. David is a remarkable academic, scientist, engineer and scholar whose contributions will leave a long-lasting legacy. In honour of his retirement, this article provides a brief synopsis of the history of Bioengineering in Ireland and the impact and contributions David has made throughout his career.

1. A PASSION FOR FAILURE

Throughout his career, David's primary research interest was in the study of strength and failure of materials dealing mainly with engineering problems, or "Why things break". In the latter years of his research career, David took a keen interest in understanding the failure of living materials such as plants, insects, shellfish and even bamboo which is widely used as a scaffolding material in Asia. As staff members, we would always be intrigued at coffee on a Monday morning to hear about David's latest adventures of roaming the beaches of South County Dublin to collect seashells for the latest project he was working on. David was also the inaugural editor in chief of the Journal of the Mechanical Behavior of Biomedical Materials from 2007 to 2015. This was an important journal for the field focusing on understanding mechanical deformation, damage and failure under applied forces, of biological material and biomaterials.

2. FROM THE LECTURE HALL TO THE COURTROOM

David has always had that special talent as an educator, to make engineering problems interesting and bring real world examples into his lectures. David taught materials, forensic materials and introduction to professional engineering to thousands of students over four decades. As undergraduate students of materials we had the privilege of hearing about the latest forensic cases David was working on. Although his questions were sometimes difficult to interpret with limited information given! "A wheel comes off a car in Spain- Why?" But that was David's way of teaching young engineers that most engineering failures are poorly defined, and we must try and use our engineering knowledge, estimations or assumptions and piece it all together to answer the question. Former undergraduate students can fondly remember one of David's favorite sayings in lectures- "The things I say are more important than what you write down"- How right he was!

Entering David's office in the Parsons building was like venturing into Aladdin's cave, there was always something interesting, unusual yet fascinating to be seen. David spent hours staring down the microscope in the corner of his office, examining a hip prosthesis or some other broken object for his latest forensic case. It was fascinating to listen to David explain his hypotheses of failure. From ladders to water boilers, to hip prostheses, surgical meshes, wine bottles to toilets; the variety of objects that David examined and studied as an expert witness for his latest court case was amazing. He truly was Trinity's own Sherlock Holmes. David was always willing to teach and as graduate students many of us will remember him running an optional lunch time series of lectures that were as enjoyable as they were educational. A wonderful colleague, open with advice, always with a measured opinion and a depth of knowledge that is so impressive yet never intimidating.

David wasn't well known for his passion for administration, but despite this, David took on the role of head of discipline in 2010. David was always cool, calm and collected. Nothing seemed to faze him, nothing was really a problem. He was a great mentor, always making himself available to junior staff, helping them set their careers in motion. There are many of us who owe David a debt of gratitude for his mentoring and supervisory skills. David has supervised dozens of PhD students over his career, many of whom were financially supported through his forensic activities and adventures as an expert witness and consultant, who have had incredible success in their own careers.

3. ESTABLISHING THE BIOENGINEERING RESEARCH CENTRE AND BIOENGINEERING DESIGN FORUM

David was inducted into the world of bioengineering through his involvement with Brendan McCormack at the Blackrock Bioengineering Institute working out of the Blackrock Clinic. Funding was won from Enterprise Ireland (Forbairt as it was then called) in 1985 and Jean Marc Moalic was a French student who undertook a Masters project with David and Brendan to research into fibre-reinforcement of bone cement. Brendan had other links with Trinity College Dublin (TCD), working with Dermot Geraghty on blood measurement devices for surgery and with the technical team in developing new walking aids. David was the 'route in' to TCD for these collaborations. When Brendan joined the Department of Mechanical Engineering at University College Dublin (UCD) in 1989 the relationship further developed, and David and Brendan established the Bioengineering Research Centre (BRC). This was a grouping of engineering departments from TCD and UCD including members from the Royal College of Surgeons (RCSI) and various medical and dental practitioners [1]. The BRC was active in many areas ranging from basic to long term research and working with many of the medical device companies in Ireland. To promote and foster engagement and interaction between engineers and other clinicians, the Bioengineering Design Forum was established and monthly meetings were held in clinical settings around Ireland providing the means to identify, share and tackle real-world clinical bioengineering challenges [2]. David had come to Trinity with a PhD in fracture mechanics from Cambridge and Brendan had studied bioengineering with Van Mow at the Rensselaer Polytechnic Institute (RPI). Availing of the small grants available in Ireland at the time, the two lecturers (as they then were) brought their MSc and PhD students together to meet monthly and share knowledge and, importantly, to enable access to testing equipment in both institutions.

Ideas were wide ranging, and the objective was to pair up clinicians and engineers to develop new devices or procedures. Among others, Gary Lyons and Alan Reid of TCD were actively involved in the design of devices. Dr Alun Carr, who had only recently joined the staff at UCD, was also an active participant providing a deep understanding of bio- and implantable materials. The BRC set the foundation for what would later become the Trinity Centre for Biomedical Engineering (TCBE), as it is today. At that time and given the focus of the medical device industry in Ireland on orthopaedic devices during that era, both of them had their biomedical engineering research in the field of orthopaedic materials and implants. A collaborative and sharing culture emerged under their leadership. Several researchers who were later to establish active research groups themselves were PhD students in this group in the 1980s. The group expanded its Principal Investigator (PI) base when Alun Carr in UCD in ceramic biomaterials and Garret Lyons in TCD in engineering design joined the Centre. In 2008 Richard Reilly moved from UCD to Trinity as Professor of Neural Engineering bringing new expertise in biomedical devices to the group. The Trinity Centre for Biomedical Engineering (TCBE) emanated from the BRC and was formally established in 2002. Today, the TCBE has over 35 Principal investigators, both academic and clinical, covering a wide diversity of research themes, including tissue engineering, neural engineering, biomechanics and medical device design.

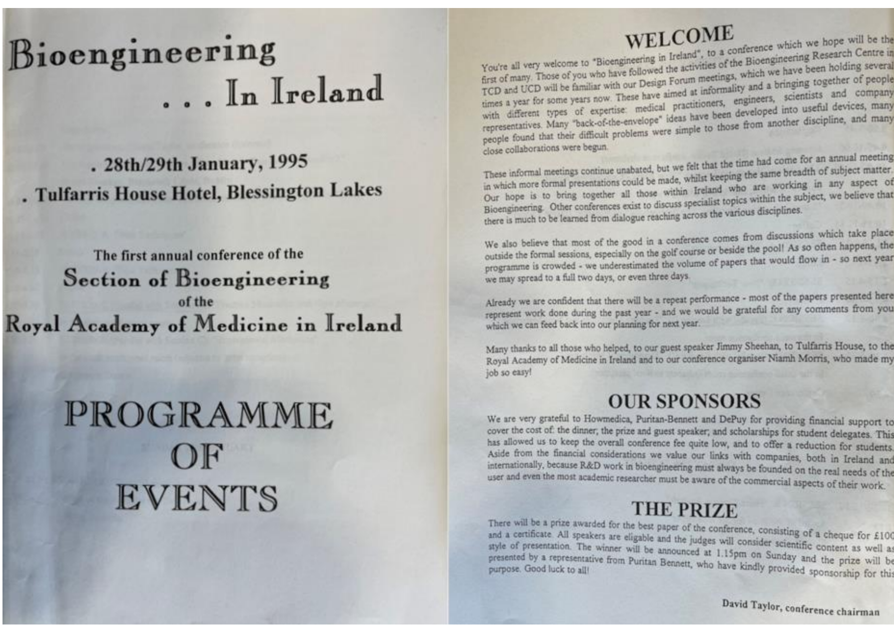
4. BIOENGINEERING IN IRELAND – A LONG LASTING LEGACY

Perhaps one of the greatest impacts of David's legacy will be the co-founding of Bioengineering in Ireland (BinI) together with Brendan McCormack. Alun Carr was involved from an early stage and together with Prof. Clive Lee, and Tim McGloughlin of the University of Limerick (UL) formed the nucleus of a national conference to bring together academic researchers and clinicians interested in a wide range of bioengineering matters. In those early days, the eligibility requirement to attend the conference was to be able to deliver a party piece – be it a song, playing an instrument or otherwise making an exhibition of oneself!

David's BinI talks were always hugely engaging including talks on the fracture toughness of eggshells to the critical distance method applied to cricket legs. BinI became an annual national conference run under the auspices of the Royal Academy of Medicine in Ireland (RAMI), which brings the biomedical community of Ireland together each year providing the platform for students and investigators to engage and share their latest and exciting research findings.

David is a fellow of the Royal Irish Academy (RIA) and RAMI and served as President of the Bioengineering Section from 1994-1996. The RAMI also approved a silver medal for the keynote lecture (named after Samuel Haughton) at the annual conference thus establishing, or validating, the subject of bioengineering in the eyes of the biomedical research and medical community. It was decided that the medallists would alternate between an engineer and a clinician and David chaired the inaugural meeting in Wicklow in 1995 (Figure 1) with orthopaedic surgeon, James Sheehan, receiving the accolade as the first Haughton Lecturer [3]. We also had the honour of David delivering the Samuel Haughton lecture in 2006 in recognition of his significant contributions to Biomedical research in Ireland. While David's achievements are certainly admirable, I think many of us will fondly remember David for the extraordinary lengths he went to dressing up for the "themed" social evenings each year. From Hawaiian nights to James Bond, David always went the extra mile and dressed to impress.

BinI, supported by the RAMI, is still running today and the 27th Bioengineering in Ireland Conference took place in May 2022 chaired by Prof. Laoise McNamara in the National University of Ireland, Galway, herself a TCD and TCBE PhD graduate.



Bioengineering

. . . In Ireland

. 28th/29th January, 1995

. Tulfarris House Hotel, Blessington Lakes

The first annual conference of the

Section of Bioengineering

of the

Royal Academy of Medicine in Ireland

PROGRAMME OF EVENTS

WELCOME

You're all very welcome to "Bioengineering in Ireland", to a conference which we hope will be the first of many. Those of you who have followed the activities of the Bioengineering Research Centre in TCD and UCD will be familiar with our Design Forum meetings, which we have been holding several times a year for some years now. These have aimed at informality and a bringing together of people with different types of expertise: medical practitioners, engineers, scientists and company representatives. Many "back-of-the-envelope" ideas have been developed into useful devices, many people found that their difficult problems were simple to those from another discipline, and many close collaborations were begun.

These informal meetings continue unabated, but we felt that the time had come for an annual meeting in which more formal presentations could be made, whilst keeping the same breadth of subject matter. Our hope is to bring together all those within Ireland who are working in any aspect of Bioengineering. Other conferences exist to discuss specialist topics within the subject, we believe that there is much to be learned from dialogue reaching across the various disciplines.

We also believe that most of the good in a conference comes from discussions which take place outside the formal sessions, especially on the golf course or beside the pool! As so often happens, the programme is crowded - we underestimated the volume of papers that would flow in - so next year we may spread to a full two days, or even three days.

Already we are confident that there will be a repeat performance - most of the papers presented here represent work done during the past year - and we would be grateful for any comments from you which we can feed back into our planning for next year.

Many thanks to all those who helped, to our guest speaker Jimmy Sheehan, to Tulfarris House, to the Royal Academy of Medicine in Ireland and to our conference organiser Niamh Morris, who made my job so easy!

OUR SPONSORS

We are very grateful to Howmedica, Puritan-Bennett and DePuy for providing financial support to cover the cost of: the dinner; the prize and guest speaker; and scholarships for student delegates. This has allowed us to keep the overall conference fee quite low, and to offer a reduction for students. Aside from the financial considerations we value our links with companies, both in Ireland and internationally, because R&D work in bioengineering must always be founded on the real needs of the user and even the most academic researcher must be aware of the commercial aspects of their work.

THE PRIZE

There will be a prize awarded for the best paper of the conference, consisting of a cheque for £100 and a certificate. All speakers are eligable and the judges will consider scientific content as well as style of presentation. The winner will be announced at 1.15pm on Sunday and the prize will be presented by a representative from Puritan Bennett, who have kindly provided sponsorship for this purpose. Good luck to all!

David Taylor, conference chairman

Figure 1. Front Cover and welcome address of the first Bioengineering in Ireland conference chaired by Professor Taylor in January 1995.

5. CASE FORENSICS IN BIOMEDICAL RESEARCH

David always has his finger on the pulse of current medical technology, and in particular testing devices which may be questionable in terms of performance. One recent example of this is his work on transvaginal meshes.

Since 2005, meshes have been used to augment transvaginal repair of pelvic organ prolapse (POP) in the United States without clinical safety and efficacy data [4]. In 2008, the FDA released additional information on serious complications associated with surgical meshes placed transvaginally to treat stress urinary incontinence (SUI) and POP due to mesh erosion, and the first lawsuits went to trial in 2012 relating to the severe consequences of using these mesh products for this application. Following requests to offer expert witness testimony for some of these lawsuits, David decided to apply his materials knowledge to explore the interaction between various different mesh materials and configurations, with muscle tissue. He has now published several papers on this work but the first paper was published in the Journal of the Mechanical Behavior of Biomedical Materials (JMBBM) and had just two authors (Figure 2) [5]. While the study is one of the first to explore the mechanism of tissue erosion for vaginal meshes and to explain the high failure rates observed with these products, another impressive and inspiring aspect of the study is that the co-author of this paper is a transition year student who undertook a two-week transition year work placement with David at TCD. Needless to say, her experience was transformative, and likely to influence her future career path. In January 2018, David was also part of a group that briefed politicians at Leinster House regarding the research around these devices. David has also been involved in a number of cases related to failed hip replacements. In the early 2000s, hip implant manufacturers began to market newer 'metal-on-metal' hip replacement implants that were designed to last longer than traditional 'metal-on-polyethylene' devices. Unfortunately, very high complication rates were observed following the implantation of these devices into certain patients, which was linked to implant wear and high blood metal ion levels. Based on his work in this area, David concluded that a critical failure made in the development of these implants was not undertaking robust human clinical trials prior to going to market. David featured in an Irish Times article (published in November 2018) which discussed the simulator tests that had been used during the design and testing of these implants; he commented that "It would have been a very good design process if they were designing a washing machine…They seem to have forgotten that it was going into a human being."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In vitro characterisation of the erosion of soft tissues by surgical mesh

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[b] Scoil Chaitriona, Glasnevin, Dublin, Ireland

Figure 2. A key paper led by David studying the erosion of surgical meshes published in JMBBM.

6. BUON VIAGGIO

David's second home is Italy, where he spends several relaxing weeks each year with his lovely wife, Niamh. David is fluent in Italian and was a Visiting Professor at Politecnico di Torino, Italy in the late 90's and early 2000's. He was a distinguished Visiting Professor at the University of Ferrara and an Honorary Member of the Italian Group of Fracture since 2009. In his downtime, David is a budding artist, and many of his abstract art works were displayed on the walls of his office, inspired by his love of nature and materials. David has also actively participated and worked on art exhibitions such as the Maple Project with artist in residence Olivia Hassett, who has contributed a chapter in this Festschrift.

It is clear that David has had a significant impact on Bioengineering in Ireland through his varied activities in the lecture hall, laboratory and beyond. He has achieved far more in his career than can be captured in this book alone. Suffice to say that David is that special type of academic that has inspired many and has had a major impact on the field of Bioengineering. It has been an honour and a privilege to have been taught, mentored and worked alongside David. We wish you the very best in the next chapter of your life. Buon viaggio!

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DEPARTMENTAL LIFE AND TEACHING AT TRINITY COLLEGE DUBLIN

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ABSTRACT

David Taylor has been variously my teacher, Head of Department and colleague for almost 30 years. He has been a major positive influence on me. While others will rightly focus on his internationally recognized research, it is my pleasure to reflect here on my experience of his teaching and general contribution to Engineering at Trinity.

1. INTRODUCTION

David Taylor has been variously my teacher, Head of Department and colleague for almost 30 years. During that time, we have had countless interactions which have collectively had a significant positive influence on me, for which I'm very grateful. It is therefore my pleasure to reflect here on my experience of his teaching, his contribution to our Department and to our collective research pursuits. I address the following topics:

- My experience of David's teaching
- An academic role model
- A life in teaching
- Legacy to engineering at Trinity

2. DAVID'S TEACHING

David joined the Engineering School at Trinity in 1983. Our long-standing colleague Paul Normoyle (chief technical officer specialist) recalls him arriving with a van at the Parsons Building from Cambridge to unload equipment.

David has done a lot of teaching. Over five decades, he has taught materials to both undergraduate and postgraduate students and he has at times also taught biomechanics, manufacturing technology and solid mechanics. Further, he has taught materials to physics and chemistry students at Trinity, and he has lectured on materials to students from the National College of Art and Design. As visiting Professor, he has taught advanced courses in fracture mechanics and failure analysis at Polytechnico Di Torino and the University of Ferrara. He knows how to teach about materials.

I was first introduced to David in the third year of my BA BAI degree in mechanical engineering at Trinity in 1993/1994, when he taught a course on materials to about fifty of us. Figure 1 shows my year's BA BAI graduation photo, and also a timeless photo of David. Suzanne O'Rourke (now a medical devices consultant[1]) recalls fondly how David always seemed available to help with a grin, even when gently chastising students for ignorance on some fundamental topics such as the meaning of yielding in materials. Suzanne also recalls the "simplicity" of his explanations of difficult technical concepts. Years later, David visited Suzanne at Boston Scientific in Clonmel to assess some unusual product failure cases, illustrating his relevance to industry despite apparently being a pure academic.

His materials course in 1993/1994 was based on a pair of concise textbooks by Ashby and Jones [1,2], and it was my introduction to materials and failure mechanics, in particular Griffith's theory of fracture. David certainly had an idiosyncratic look and manner: my memory has him wearing green jeans, sandals and socks, a multicoloured jumper, his beard and his trademark waist pouch from which he would fish out various implements. The look was of a scattered academic, but the mind was razor-sharp. There was general consensus that he gave excellent lectures.

With the benefit of hindsight, I see that David understood early the need to deliver a show as part of teaching, and over the years I have seen him switch from conversation mode to performance mode as he strode to the lectern to deliver his talk at a conference or seminar series. While I did not follow him sartorially, I understood from him the importance of the performance aspect to teaching.

[1] Triskele Consulting | Medical Device Consultant | Ireland (triskele-consult.com)

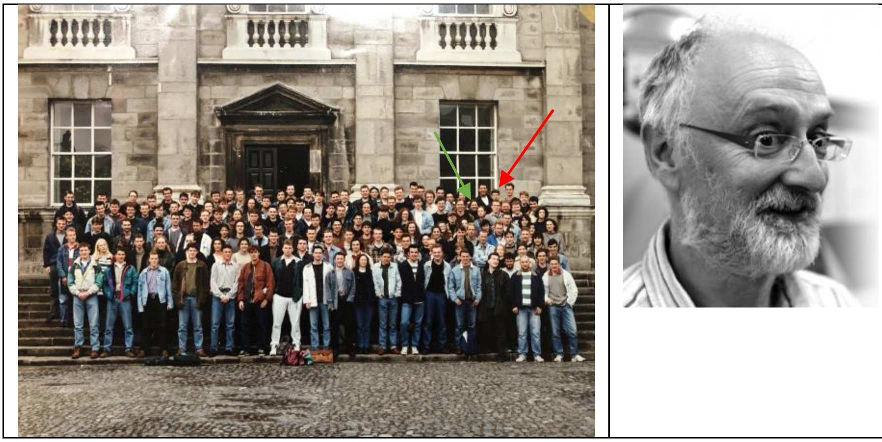

Figure 1. The BAI graduation photo from 1995 on the TCD Dining Hall steps (red arrow points to Ciaran Simms, green arrow to Suzanne O'Rourke) and a timeless headshot of David Taylor.

David unnerved us as students because his very enjoyable lectures were followed by really tricky examinations. He focused on setting unseen real-world problems relating to materials and failure, which rendered rather ineffective our standard examination revision model of working through previous tutorials. His approach caused me to reflect on just how challenging it can be for a young engineer to put a body of theoretical knowledge into practice. Today I teach a module on rigid body mechanics to our third-year cohort [3], and I see similar challenges in analysing forces in unseen real-world applications. A well-formulated free body diagram is a beautiful construct, but students do not find it easy to conceive. Although perhaps pedagogically naive, practice and repetition seem to be the key to success in this as in many other things[2].

3. AN ACADEMIC ROLE MODEL

David's natural inquisitiveness is an inspiration to many. I recall a conversation with him in the early 2000s when I had recently joined the department as a young lecturer. I wasn't sure how to pitch my research and he said something to the effect of "don't worry, you can focus on anything you like… after all, most things are not known". The idea of most things being unknown widened my horizons and came as both a revelation and a liberation, self-evidently true once pointed out, but not a conclusion I could naturally draw myself at that time.

David played a major role in the transition in our department to a strong emphasis on published research. This is so pervasive now that it is perhaps hard to appreciate that this was not always the case. I clearly recall being in

[2] I think of this when we "tick off" certain learning outcomes as having been "achieved" during professional accreditation cycles for our degree programmes.

awe of David's ability to produce multiple journal papers in one year, and feeling a sense of responsibility to attempt to follow this lead. While David never put overt pressure on others (that would not be his style), his leadership by example left its mark. My primary mentor was Garry Lyons (whom we were able to honour with a Festschrift of his own in 2008 [4]), but David and Patrick Prendergast both played a major role in helping me and others meet our potential.

David and I share a common interest in human tissue mechanics, though I have focused on soft tissues and he on hard tissues. We did collaborate once, addressing the fracture toughness of muscle [5]. We also both served as editors on the Journal of the Mechanical Behaviour of Biomedical Materials, which he founded. This led to many interesting discussions regarding decisions on individual papers and some entertaining reviewer/author exchanges.

I think David had an uneasy relationship with funded research and funding agencies, especially those seeking short-term impact. I recall him offering the view that it is not possible to know what the future utility of current research findings will be, and that people should therefore just be left to pursue their interests free of a utilitarian justification. In the end, I think David achieved this for himself largely by funding his own research through consultancy work. This had the added benefit of also providing him with many interesting real-world questions.

David is (I think) also sceptical of academic empire building, and he himself epitomizes the teacher/scholar model which is increasingly difficult to maintain today.

I have often participated with David on student project evaluations. The stakes are high for the student. In these settings, David is in his element. He excels at showing genuine interest in each new research area, sets the student at ease with his naturally casual style and then plants a series of questions starting with the fundamentals but quickly probing the limits of the student's understanding of the topic. I have been at the receiving end of this, and I have watched it also from a safe distance. He shows a remarkable skill in remaining friendly while cutting through any bluster very quickly.

David did not actively seek administrative leadership positions within the University, and he openly acknowledged his preference to focus on his research and related teaching. However, when he did take on the role of Head of Discipline in 2010, he did this effectively and with good cheer. It seemed that he knew well what our main priorities should be (focus on teaching and research and letting colleagues get on with things) and he actively resisted managerialism. I think his guiding philosophy was to protect colleagues from as much bureaucracy as possible, for example by completing information requests on our behalf with an educated guess on what he thought we were doing, rather than requiring us to report on what we were actually doing. I was grateful to him then and as current Head of Discipline, I'm conscious of the benefits of this approach.

It seems to me that David never struggled with self-confidence, but he combined this inner self-assurance with a commitment to democratic principles, such that his leadership was never confrontational.

4. LIFELONG TEACHING

David developed a unique teaching module on forensic materials engineering about fifteen years ago [6], in which he applied the flipped classroom approach. He taught this through a series of case studies driven by his own consulting and research work. This module is a great example of research-led teaching and has long been popular with the students. Sensing this, David has continued to teach this module beyond formal retirement, and we are grateful to him for this. It is not a module that could be taught by any of our colleagues, and it has achieved great feedback again this year.

David has also made a significant contribution to teaching our first- and second-year cohorts through a number of modules (Junior Fresh Introduction to Professional Engineering [7] & Senior Fresh Materials which is not presently running). These modules feature seminar style lectures from which thousands of engineering students have learned about these topics from him.

5. LEGACY

David has made a long and lasting contribution to Engineering at Trinity. He started biomedical engineering research at Trinity in the 1980s, a branch of engineering that has since grown dramatically with huge contributions from a cohort of colleagues. We now have a dedicated stream of biomedical engineering on our BAI/MAI programme [8], an MSc in biomedical engineering [9] and a research centre for biomedical engineering [10]. There has been serious discussion about founding a separate department of biomedical engineering, but for now this teaching and research strength is recognized in our belated name change in 2020 to the Department of Mechanical, Manufacturing and Biomedical Engineering.

6. CLOSING REMARKS

With David's retirement, I am forced to face the reality that, of the cohort of current colleagues who taught me as an undergraduate, only Henry Rice and Dermot Geraghty remain as full-time academic colleagues at Trinity. I often think about the department and the college as it is now and how it has been shaped by the people who worked in it in the past. I am reminded of the hereditary integral often used to characterize stress-strain behaviour in viscoelastic materials, whereby the current state of the system is a function of all the previous contributions to changes in that state, each change subject to a decaying exponential and weighted to signify its relative importance. While none of us can ultimately avoid that decaying exponential, David's weighting is appropriately high. He has made a singular contribution to Engineering at Trinity, and we are grateful that he continues to build on that with us.

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SOME REFLECTIONS ON DAVID TAYLORS CONTRIBUTION TO TRINITY COLLEGE DUBLIN

Patrick Prendergast

Research Professor and Provost (2011-2021), Trinity College Dublin

ABSTRACT

I have known David Taylor from almost the start of his Trinity career: first, as an undergraduate attending his materials science lectures in the Old Chemistry Lecture Theatre; next, as one of his PhD students with an office beside his on the third floor of 24 Lincoln Place; then, as an academic colleague in the Parsons Building, and finally, as Provost, meeting him mostly at committees or college dinners. I am privileged that David was my PhD supervisor; he had his own unique style that was both laid-back and results-orientated. It was an effective style judging by the number of research students who successfully completed their research degrees under his supervision. I learned much from him then, and in the years since.

1. INTRODUCTION

When David Taylor joined Trinity College Dublin in Hilary term 1983, there were 437 full-time academic staff and 7,041 students in the university. The Department of Mechanical and Manufacturing Engineering had some 20 staff (11 academic, 7 technical, and 2 administrative and supportive). There were no postdocs. On the day of David's retirement in September 2021, there were 952 full-time academic staff and 18,871 students in the university. The department had 53 staff (26 academic, 8 technical, 3 administrative, and 16 postdocs). These numbers show that a great change happened in Trinity in the almost four decades since 1983. Much is written about change in universities – but not so much is written about what stays the same. In my contribution to David Taylor's Festschrift, I would like to write about what is or should be constant in the life of universities in the context of his contribution to Trinity College Dublin generally. In doing so, I can only hope that my views in this regard do not differ too much from his own.

2. TEACHING AND RESEARCH

One of the many facets of David's career to admire is the way he lives up to the challenge of research-led teaching. In my Senior Sophister year I took his final-year course on 'Strength and Fracture of Materials'. His lectures were very well prepared, with a typescript for his course material given to us at the start of the course. The typescript incorporated his own research and it contained information that was not to be found explained in the same way in the textbooks. I'm reminded of the story often told that lecturers come in three types: those that teach to the textbook, those that write the textbook, and those who don't believe in textbooks at all. Looking back on David's typescript from 1986, which I still have, it is impressive that a lecturer – a young one in his first teaching post – should have given such care to producing notes that were reflective of his own thinking on the subject. It is a measure of how seriously he took his teaching/research as a unified activity, and it is something that I know he has replicated time and time again in the courses he has delivered since then.

The teaching/research nexus is one of the great features of a university that should never change. However, research was not always thought to be important in a university. It was Von Humboldt who first articulated the idea of a university as a place of research, and the idea took root in the German universities at the beginning of the 20th century. The idea spread around the world and became the progenitor of the modern American research university, and now forms the basis of universities in countries across all continents [1]. It is the reason that universities are now central pillars of social and economic change in the societies they serve. Von Humboldt's idea has won out over Newman's idea of a university as a place for students to debate and socialise together, although that is important as well.

The reason research and teaching are bound up together is not just that students should be taught the latest research results. It is because it is important that students learn that knowledge is always changing; knowledge is not a static corpus of information to be learned off by rote, it is ever-changing and dynamic, continuously added to and continuously contested. In their own learning, students should not be afraid to question existing knowledge and they should take every opportunity to add to the body of knowledge in their discipline. Learning should be a training in thinking because "Thinking is one of the chief pleasures of the human race". A university education should develop independence of mind and it should imbue students with a desire to continue learning when they leave the university. Such ideas need their advocates in third-level education, particularly if the needs of employers are held to be the supreme arbiter of what should be taught to students. Of course, the needs of employers are important and the curriculum should, certainly in an engineering school, be relevant to industry.

3. MANAGEMENT AND ADMINISTRATION

Universities need to be administered. There is no getting around it: staff need to be hired and paid, timetables need to be set, assessments need to be held, and all need to be done in suitable buildings that must be bought, fitted out and maintained. While university administration is necessary, individual academics can successfully minimize their exposure to it. Some academic colleagues consider it a great achievement to avoid administrative roles altogether. However, if academics avoid administration entirely then the university will not run smoothly. It is certainly true that the compliance culture of modern times has led to far more administration in a university than most people now think reasonable, and the extent of it is now a burden on both professional and academic staff. It seems to me that this burden will not abate any time soon because the State requires ever more knowledge of how expenditures are incurred; we must resign ourselves to the fact that the freedom we have to teach and conduct research comes at the price of having to administer, and we must design systems to do it as efficiently as possible. We must judiciously balance academic duties so that the leadership of a university is exercised by academic and professional staff acting together. This is no easy task. The collegiate model of Trinity leadership aims to achieve this balance by electing academic colleagues to fulfil the roles of Head of Department, Head of School, Faculty Dean, and Provost. This electoral process is unique in Ireland, and perhaps is unique in the world. Colleagues are elected to fulfil management roles for a period, usually between three and six years. David served as Head of the Department of Mechanical and Manufacturing Engineering from 2010 to 2013. I don't know if he loved it or hated it but at least he did it. I am reminded of the lines of the poet W.H. Auden: 'When there was peace, he was for peace; when there was war, he went.'

I believe academics' willingness to step into management roles, either through appointment or election, as and when the need arises, and at an appropriate stage in their careers, is a crucial element in sustaining the autonomy of universities, and ultimately the continued exercise of academic freedom.

4. COMMITTEES AND GOVERNANCE

There is an old joke that a university is a group of people linked together by a common central heating system. Another version is that they are linked by a committee system. Most academics would probably place greater value on central heating than on committees, but a university can do without neither.

Committees are usually created with good intentions. They allow many people to have an input into decisions; they allow many disciplines and staff groups to be represented; and they increase transparency. Laudable though these three intentions are, they can have three negative consequences: viz, no one person is responsible for a decision; people participate in committees to keep an eye on colleagues from other departments; and we implicitly tell academic managers that we do not trust them if we ask that every decision they make is discussed and documented before a committee.

At the highest level in Trinity, the College Board and its principal committees and the University Council and its academic committees, provide governance. It is probably fair to say David Taylor did not go out of his way to serve on committees, but he ended up on many in any case. I served with him on some of them, most recently the Personal Chairs review committee. I admired greatly the conscientious consideration David gave to each case, and I felt his pain sometimes at decisions that had to be made given financial constraints imposed by the Board.

University committees are much maligned and it seems no one has a good word to say about them. In Franz Kafka's *The Penal Colony* the captain extols the virtues of a machine which executes prisoners by inscribing their crimes onto their bodies. Maybe this is not a bad metaphor for the university committee system. I think there could be fewer committees, but this would mean trusting academic managers to make decisions without the requirement to have each one discussed at a committee beforehand. Collegiality and committees go together and we in Trinity, as in all organisations, must balance one with the other.

5. FELLOWSHIP AND SENIOR FELLOWSHIP

'Fellowship' is an essential institution of Trinity College Dublin. It was brought into existence with the foundation of the college in 1592 when the first three Fellows were named in the Royal Charter of Elizabeth I. The Fellows have elected additional Fellows ever since, in a perpetual succession [2]. Fellowship in Trinity is quite an exceptionally durable institution.

From 1637 the seven longest-serving of the Fellows were co-opted as Senior Fellows (SF) with the remainder then designated as Junior Fellows. The Senior Fellows, together with the Provost and, following a reform in 1911, a number of elected Junior Fellows and non-Fellow Professors, constituted the Board of the College [3]. After the Universities Act (1997) the Senior Fellows ceased to have an automatic right to Board membership, but being a Senior Fellow still continues to be a mark of the highest seniority in the college community. Senior Fellows are regularly asked to deputise for the Provost or Vice-Provost at Commencements or other ceremonial events.

Election as a Fellow of Trinity College Dublin (FTCD) follows from a recommendation of the Central Fellowship Committee (CFC) to the Board. The CFC's main criteria for election are published work that demonstrates a strong international reputation for research, and a high standing for scholarship among one's peers. The annual competitive process for Fellowship incentivises academics to maintain a focus on research at the early-to-mid stage of their careers, at a time when many might be tempted to rest a bit having obtained a tenured academic post. Fellowship also provides recognition among the college community. David was elected FTCD in 1989. By virtue of his early election to Fellowship he remained long enough in the ranks of the Junior Fellows to be co-opted a SFTCD in 2015.

What are the responsibilities of a Fellow of Trinity College Dublin? As Provost, my answer to this question used to be that Fellows, more than any other body, are responsible for stewarding the college's reputation; they do this by taking action as a group if a given situation requires it, or by their individual actions as Fellows in performing statutory functions such as assenting (or not) to changes in the college statutes, or agreeing to take on one of the senior college officerships reserved for Fellows, if asked to do so by the Provost. In a larger sense, however, the pursuit of ground-breaking research and scholarship of the highest order is the truest contribution a Fellow can make to Trinity College Dublin. Fellows should feel that they have fully delivered on the college's expectation of them if their published work (or other work creating societal impact) has advanced humankind's understanding of the world for the better. Here, I add my voice to the many others in this Festschrift to acknowledge just how well our colleague and friend, David Taylor, has done this, and done it consistently over many decades through the publication of books, journal articles, and conference proceedings.

His research laid the groundwork for the development of the Trinity Centre for Biomedical Engineering which has had such far-reaching consequences for the careers of many generations of colleagues in the department and the university over the last 20 years [4]. Also important is David's work with colleagues to embed the discipline of Bioengineering, or Biomedical Engineering, within the academic firmament of the country. An essential step in this regard was taken when David, working together with Prof. Clive Lee, persuaded the Council of the Royal Academy of Medicine in Ireland to establish a Section of Bioengineering of the Academy in 1994 [5]. This allowed engineers and clinicians to share a common forum for presenting the outputs of research work. Later 'The Section' established an annual conference under its auspices called 'Bioengineering in Ireland'. Those who were present at the first of these conferences in Tulfarris House, Co. Wicklow, with Niamh Morris as the professional conference organiser, will always remember the high scientific quality of the papers presented, exceeded only by the conviviality that set the tone for the ultimate success of bioengineering as a discipline operating effectively alongside the medical device industry in Ireland [4].

6. BACK TO THE BEGINNING

A year or so into their journeys, PhD students begin to appreciate that their colleagues around the world, whose names they read on research papers, are real people – people with personalities and ideals. They begin to sense that they are working in a kind of community. It's an awakening. It's exciting to belong to a peer group of other PhD students and postdocs who work at other famous universities around the world. It's flattering that they are genuinely interested in what you're doing. It's a time to make friendships, share enthusiasms, and find camaraderie among those soldiering along in the same direction as yourself.

There are also senior professors, the big shots, throwing shapes in the background. Between them there can be a competition to be the first to make an important discovery, or a race to be ‘the first to publish’. It can be a drama. In the field of biomechanics, one of the first major conferences we attended was the Second World Congress of Biomechanics held in Amsterdam in July 1994. David managed to come up with the funds to send a large Trinity delegation, no small feat in the days when there was almost no funding for Irish science. David presented a paper himself on ‘Damage accumulation and failure prediction at stress singularities’ [6]. We met groups from US universities like Stanford, Harvard, and Columbia, and many European groups too; among the biggest were those from Nijmegen, York, Leuven, Bologna and London. They were researching and publishing on topics similar to ours. We met them at receptions and banquets, had drinks with them in the evenings in the Leidseplein, and arranged visits to their labs the following year. David sat back and let us enjoy the experience of talking science in a beautiful foreign city. He even found time to paint a street scene.

— Are you a nationalist, Mr Joyce?

— I am an internationalist, was his reputed reply.

David was turning us all into internationalists, which you have to be to be a scientist. We never looked back.

Amsterdam, D.T. '94
Watercolour
20 cm x 15 cm
private collection

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DIATOM-INSPIRED ARCHITECTED MATERIALS USING LANGUAGE-BASED DEEP LEARNING: PERCEPTION, TRANSFORMATION, AND MANUFACTURING

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ABSTRACT

Learning from nature has been a quest of humanity for millennia. While this has taken the form of humans assessing natural designs such as bones, butterfly wings, or spider webs, we can now achieve generating designs using advanced computational algorithms. In this paper we report novel biologically inspired designs of diatom structures, enabled using transformer neural networks, using natural language models to learn, process and transfer insights across manifestations. We illustrate a series of novel diatom-based designs and also report a manufactured specimen, created using additive manufacturing. The method applied here could be expanded to focus on other biological design cues, implement a systematic optimization to meet certain design targets, and include a hybrid set of material design sets.

1. INTRODUCTION

Bioinspiration has been an active field of research. Among its pioneers is David Taylor – the inaugural editor of Journal of the Mechanical Behavior of Biomedical Materials and a fixture at the regular International Conference on Mechanics of Biomaterials & Tissues. Prof. Taylor has contributed to the biomaterial's community in so many ways, including his dedication to building a strong community around the journal and the conference, from which a wide set of research contributions have spawned. To honour David Taylor, this article is dedicated to him in celebration of his retirement [1-4].

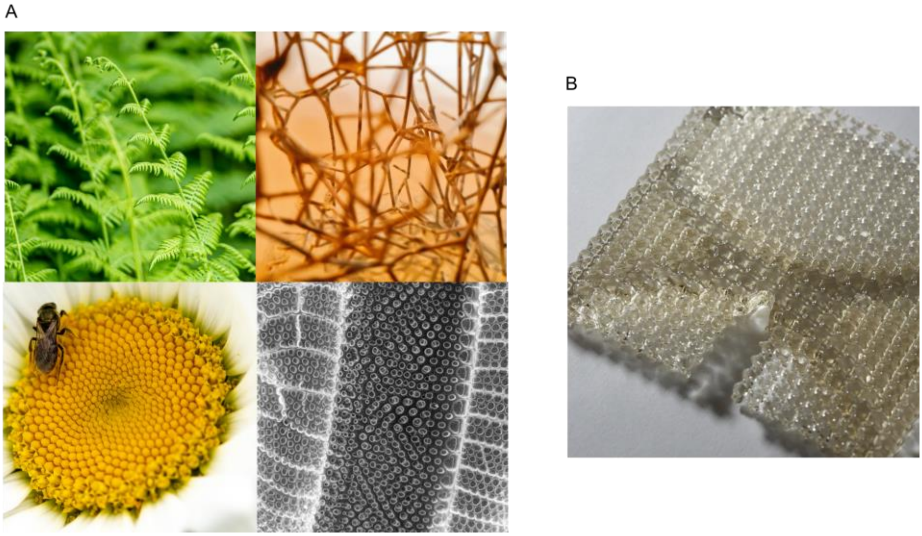

Figure 1. Hierarchical structures in natural materials (A), Fern leaves, spider web, patterns in flowers, diatom structure (diatom courtesy Picturepest - Diatom - Isthmia nervosa - 400x, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=39164600). (B) Biologically inspired material design, where a gyroid material architecture is modulated to mitigate the effects of a notch, minimizing stress concentrations.

While bio-inspired design has taken the form of humans assessing natural designs such as bones, butterfly wings, plans structures, or spider webs, and many others (some examples shown in Figure 1), we can now generate designs using advanced computational algorithms [5-10]. In this paper we report novel biologically inspired designs of diatom structures, enabled using transformer neural networks, using natural language models to learn, process and transfer insights across manifestations.

The approach used in this paper follows a similar strategy as reported in [7,10]. However, for the present study we train a VQGAN model from scratch, similar as done in [11], using a publicly available diatom dataset (*ADIAC Project (CEC Contract MAS3-CT97-01)*[12]. The examples provided here offer a perspective to consider bio-inspiration from an artificial intelligence point of view; and the integration of human language as design input exemplifies how artificial and human intelligence can work together towards innovative design solutions.

The focus of this chapter is on diatoms, given that they provide interesting multifunctional material designs. A challenge has been to translate the interesting structural features seen in diatoms into engineering solutions. One way is to extract salient features and then reconstruct bioinspired analogues; this method uses human intelligence to achieve the goal and has been widely used. Here we propose a complementary method that removes some of the human biases and gives an artificial intelligence system the task to take design cues from a library of diatom structures and convert them into a set of design solutions.

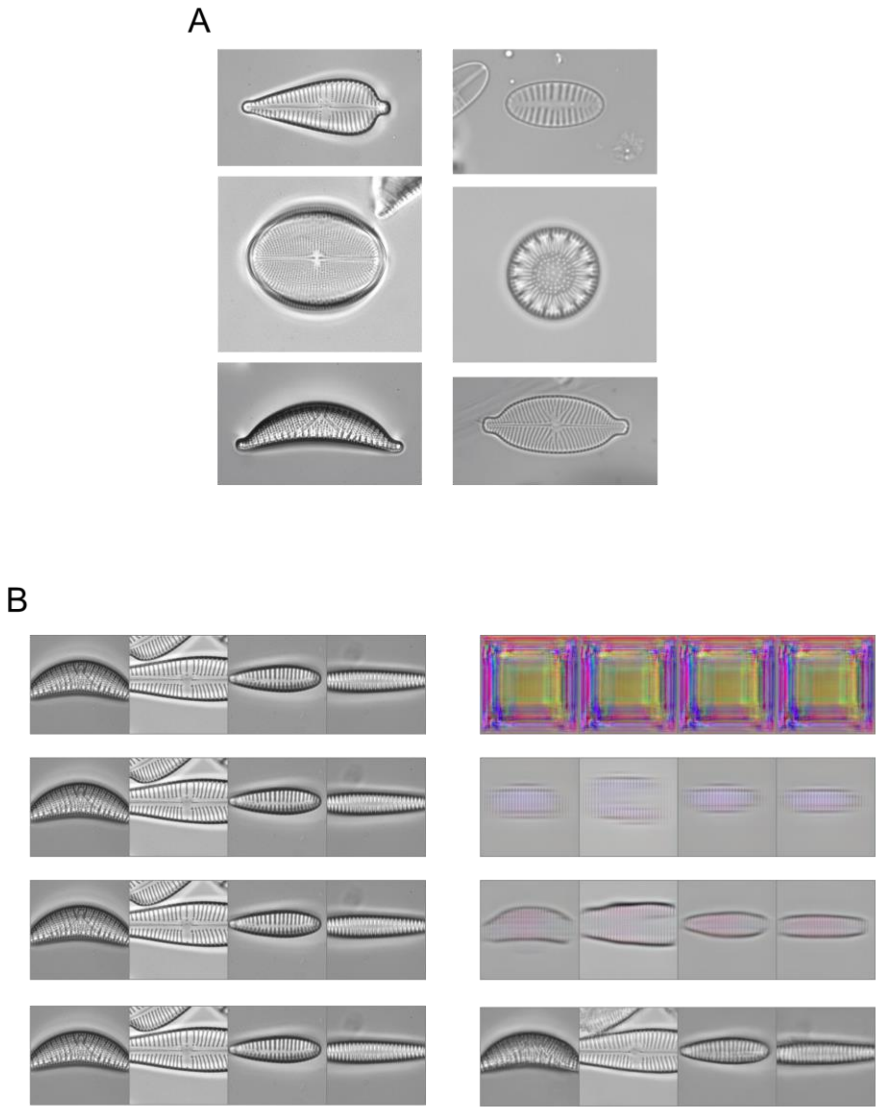

Figure 2. A, samples of diatom structures as reported in (*ADIAC Project (CEC Contract MAS3-CT97-01)*). B, training of a VQGAN model, so that it can reproduce the particular architectural details of diatom structures. At the end of the training, the transformer neural network has learned how to generate synthetic diatom structures. The samples shown here (left: ground truth, right: reconstruction) show how performance increases over a total of 200 training epochs.

1.1 Training the transformer image generation model

The first step in the approach used here is to train a neural network that has learned to generate biological designs. In the study reported here, we develop such a model by training it against a set of diatom structures as reported in (*ADIAC Project (CEC Contract MAS3-CT97-01)*[12] (Figure 2). The data is then used for training a VQGAN model [13], so that it can reproduce the particular architectural details of diatom structures. At the end of the training, the transformer neural network has learned how to generate synthetic diatom structures. The samples shown in Fig. 2B (left: ground truth, right: reconstruction) show how performance increases over a total of 200 training epochs.

1.2 Integrating the transformer model with CLIP

We now integrate the image generation algorithm with a classification method, CLIP. CLIP is a general-purpose image classifier, as reported in [14]. VQGAN and CLIP is integrated as suggested in [15].

Figure 3 depicts the overall approach similar as done in [7, 10]. Design inputs are provided via a text prompt, which the algorithm converts into a final image prediction. It is then used to generate a 3D model through a tileation and 2D-3D translation algorithm, resulting in a final material manufactured using 3D printing.

Figure 4 shows sample predictions using the trained model, for a variety of design inputs. As can be seen, a variety of structures are generated that feature aspects of diatoms, but also accomplish to represent aspects of the design cues provided. This integration of biological data, human language, and resulting designs that can be assessed and examined, offers a new approach to bio-inspiration.

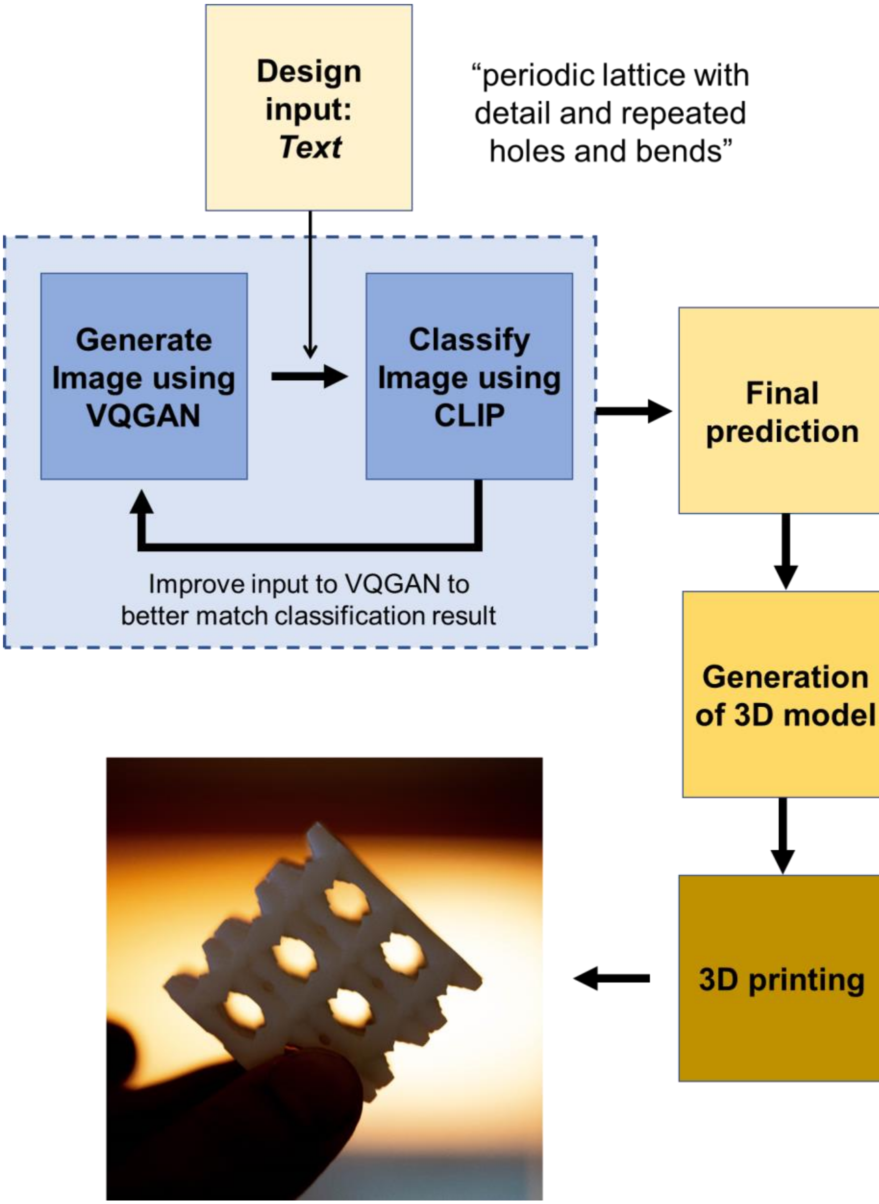

Figure 3. Overall approach following the method reported in [7, 10]. Design inputs are provided via a text prompt, which the algorithm converts into a final image prediction. It is then used to generate a 3D model through a tilation and 2D-3D translation algorithm, resulting in a final material manufactured using 3D printing.

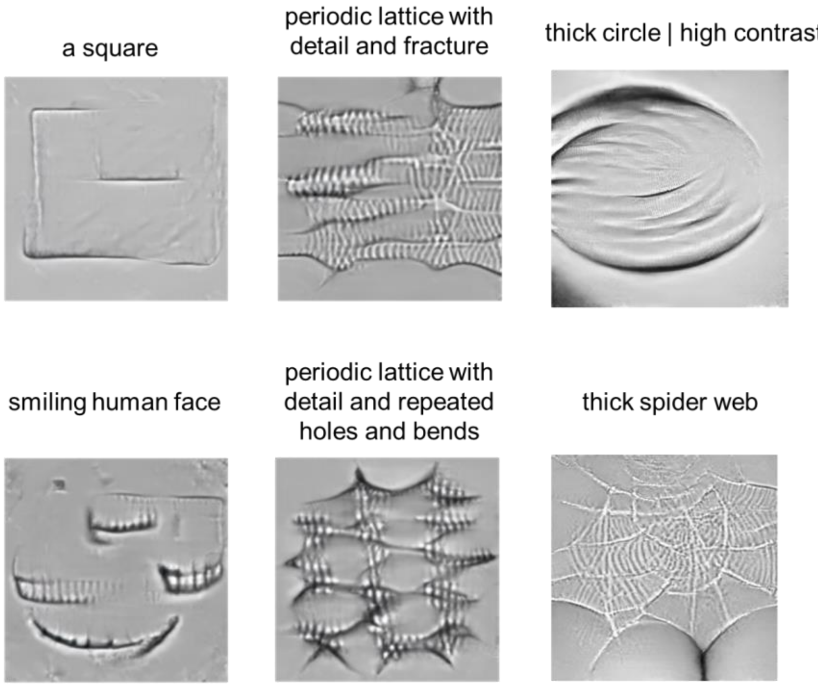

Figure 4. Sample predictions using the trained model, for a variety of design inputs. The resulting images reflect characteristic features of diatoms, but also meet the design demands given by the text prompt.

2. RESULTS AND DISCUSSION

We now present several examples of using this model to generate diatom-inspired materials that are manufactured using 3D printing. We start with a first example, shown in Figure 5, where we synthesize high-resolution images that are converted into height maps for 3D printing. This is the simplest way by which a 2D image can be transformed into a 3D material. Figure 5 shows results from two sample text prompts, including the analysis and manufactured material.

Next, we move to generate and manufacture full 3D architected materials, using the algorithm reported in [7]. Figure 6 shows Generation of 3D architected materials, using the algorithm reported in [7]. Figure 6A depicts the progression from the text prompt to the generation of a processed image, and the translation to a periodic 3D structure. Figure 6B illustrates the manufacturing method. Figure 6C shows results of a finite element analysis of the structure, exposed to tensile loading.

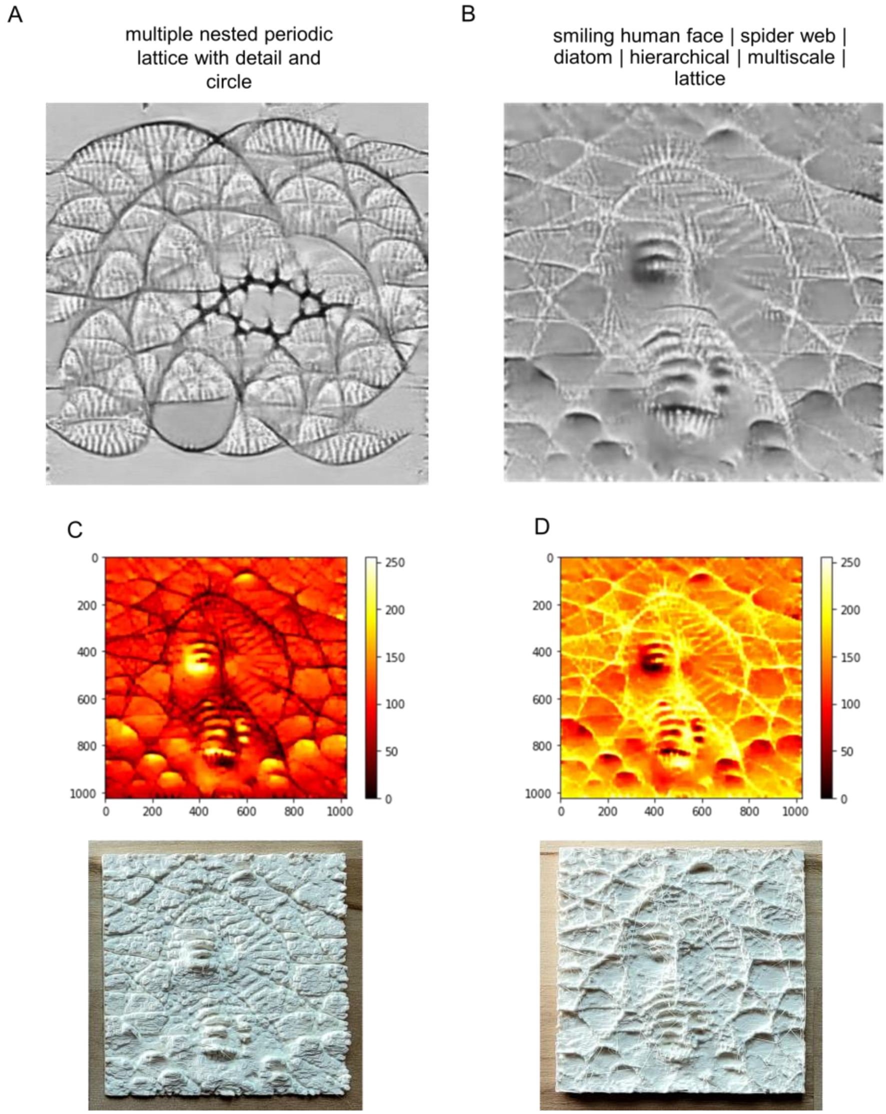

Figure 5: Additional examples, using higher resolution image output (1024x1024), which can yield results with intricate details. Panels A-B show two sample text prompts, with panels C-D showing two distinct post-processing methods. In C, a contour height map is created where dark areas are correlated with high height. In D, the inverse is achieved, where bright areas are associated with high height, forming a sort of inverse design to what is shown in C. The bottom rows show the 3D printed results (7cm x 7cm size; printed using FDM with an Ultimaker S3 printer using PLA filament).

Such analysis can provide insights into areas of large displacements, high stresses, or other mechanical measures. The finite element analysis is conducted using an isotropic material model where the material parameters are chosen to match the datasheet of the Ultimaker PLA filament.

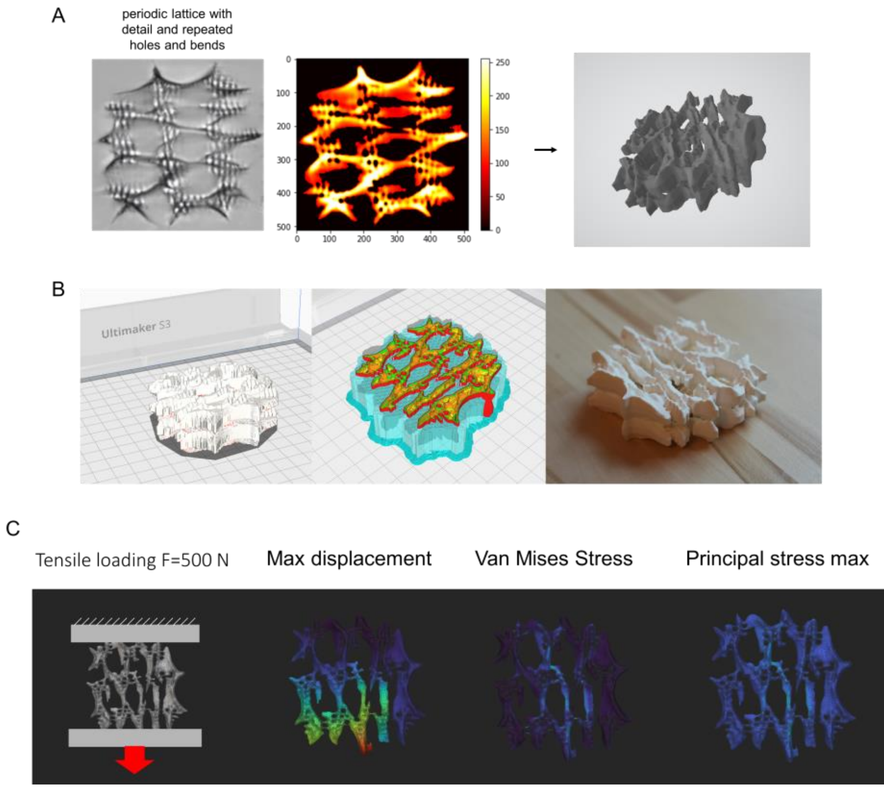

Figure 6: Generation of 3D architected materials, using the algorithm reported in [7]. Panel A shows the progression from the text prompt to the generation of a processed image, and the translation to a periodic 3D structure. Panel B shows the manufacturing process by which the material is made experimentally (cross-dimensions 7cm x 7 cm; printed using FDM with a Ultimaker S3 printer using PLA filament and PVA as support material to realize the complex 3D geometry). Panel C shows a finite element analysis of the structure (performed using a static analysis via the *nTopology* software, exposed to tensile loading. Such analysis can provide insights into areas of large displacements, high stresses, or other mechanical measures.

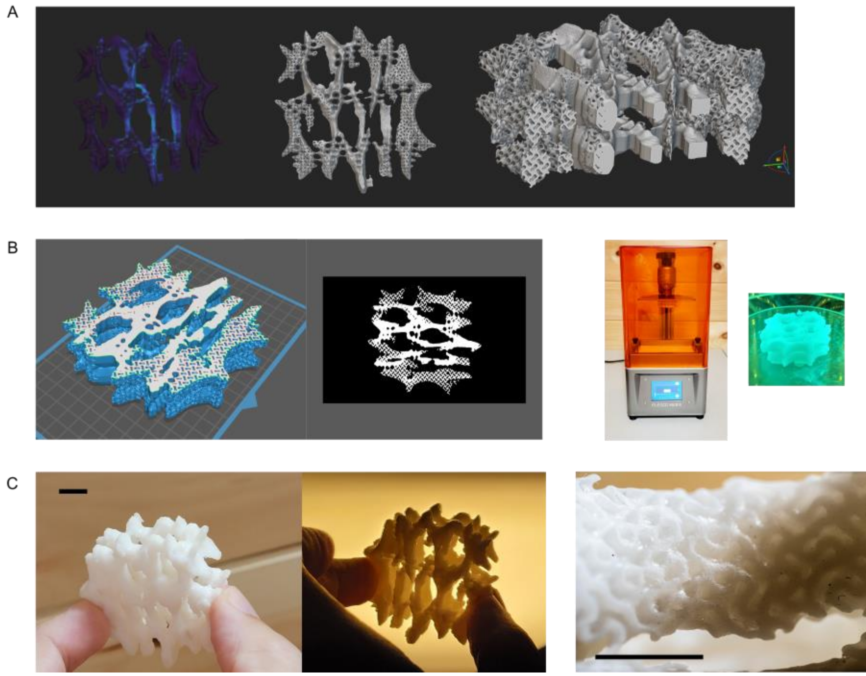

Figure 7: Generation of multi-level architected material. (A) shows how the Van Mises stress distribution is converted into a field map, which in turn is used to modulate the thickness of a gyroid microstructure. Areas of high stress yield solid material, and areas of low stress a highly porous material. The cross-section (A, right) shows this internal microstructure distribution. (B) Manufacturing of the resulting material design using resin printing (ABS-like resin; printed using an Elegoo Mars printer and subsequently cured in a UV bath). (C) Resulting material with multilevel material architecture; left: overall specimen (scale bar 1 cm), middle: different perspective against background light to visualize the internal structure. Right: Macro-view of the internal gyroid structure in an area of high porosity (scale bar: 5 mm).

The design reported in Figure 6 reflects a form of a synthetic diatom. However, it does not yet possess internal structure. One way to add another level of hierarchical structuring is to use the stress field resulting from the finite element analysis shown in Figure 6C as an input to modulate a porous gyroid microstructure**.** Figure 7 shows results of generation of such a multi-level architected material. Figure 7A shows how the Von Mises stress distribution is converted into a field map, which in turn is used to modulate the thickness of a gyroid microstructure. Areas of high stress yield solid material, and areas of low stress a highly porous material; the cross-sections directly visualize the multi-level structure obtained in this way. Figure 7B shows the results of manufacturing of the resulting material design using resin printing. Figure 7C shows images of the resulting material with multilevel material architecture; left: overall specimen (scale bar 1 cm), middle: different perspective against background light to visualize the internal structure. Right: Macro-view of the internal gyroid structure in an area of high porosity (scale bar: 5 mm).

Figure 8 shows another example of using a simpler design as an elementary unit cell, rendered fully periodic and tileable in 3D to generate a block of architected material (4cm x 4cm x 4cm). Figure 8A, left shows the design cues, the unit cell (middle), and the resulting design as an architected material cube. Figure 8B offers different views of the designed material and Figure 8C reveals the manufactured result, showing the intricate internal structure.

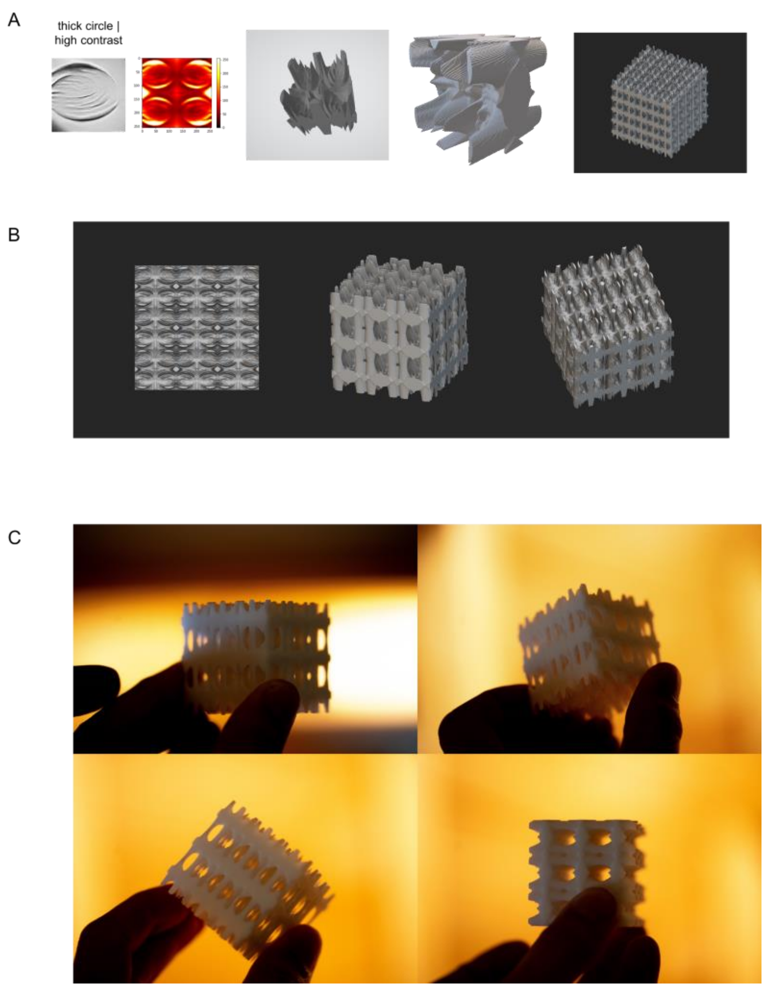

Figure 8: Another example of using a simpler design as an elementary unit cell, rendered fully periodic and tileable in 3D to generate a block of architected material (4cm x 4cm x 4cm). (A) left shows the design cues, the unit cell (middle), and the resulting design as an architected material cube. (B) Different views of the designed material. (C) Manufactured result, from different angles, showing the intricate internal structure.

3. CONCLUSION

In this chapter, a method to translate biological structural data – here, diatoms, is applied to generate various biologically inspired designs. The various results showed that natural materials provide a rich set of inspiration and how 3D printing (both resin-based and fused-deposition modelling (FDM)) can be powerful tools to manufacture resulting designs.

The method applied here could be expanded to focus on other biological design cues, implement a systematic optimization to meet certain design targets, and include a hybrid set of material design sets.

Future work could also focus on testing some of the resulting materials and compare against simulation results. An area of particular interest could be to test fracture properties to better understand whether the porous geometry of diatoms [16, 17] realized through this deep learning enabled translational approach can yield interesting new properties.

The intersection of artificial and human intelligence is an exciting frontier that offers a platform for novel solutions; especially, converging towards new methods that systematically mine natural material data for incorporation into synthetic design solutions. Not only can such work advance our fundamental understanding of biological design principles, but also further our capacity to combine knowledge in existing engineering theories with evolutionary concepts.

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WHERE SCIENCE AND ART MEET

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ABSTRACT

This contribution tracks the collaborative journey that David Taylor and I have shared since 2013. During the seven years plus of our working relationship David was always quick to share his scientific expertise and always on hand to offer help and inspire my artistic practice. This article points to David's inquisitive nature and the interest and time that he has invested in exploring the fertile ground where science and art meet. Common interests in notions of fragility are interwoven throughout the various projects that we were involved in. For this article I will focus on the three main art and science projects that we worked on together.

1. EXPLORING THE GROUNDS FOR A COLLABORATION

In 2013, via a kind referral by artist Grace Weir, my search for a scientist interested in collaborating with an artist ended when I was introduced to David Taylor. Immediately we set about getting to know each other's fields of practice. To that end we organised to meet in my studio and in David's office in the Parsons building. During several stimulating conversations, a common interest in exploring notions of strength and fragility emerged. This exploration over the years manifested firstly with an interest in the fragility of the human body and its skeletal structure and subsequently led to the exploration of a selection of the trees of Trinity College Dublin.

2. THE EXOSKELETON COLLABORATION

2.1 The development of a hypothetical exoskeleton by David Taylor

During our early meetings David talked of his interest in how the human skeleton is designed to be structurally strong and support the human body from the inside. Ironically though this skeleton does not protect some of our most important major organs.

After much discussion we found ourselves exploring hypothetical notions about what it would be like if humans evolved to have an exoskeleton. David began to investigate how the shape and structural integrity of the human skeleton would change as it evolved from an endo into an exoskeleton. He explored how the mechanical workings of the muscle and tendon systems would have to alter to accommodate each step change to the human skeleton. David's scientific calculations culminated in his development and 3D printing of an exoskeleton section of the human knee joint (Fig. 1).

Figure 1. 3D printed section of hypothetical exoskeleton knee joint designed by David Taylor.

2.2 *Endo Exo* exhibition, TCD, 2014

Over the following months David's exoskeleton research inspired me to develop of a series of new artworks. Outcomes from this collaborative process including David's beautifully rendered drawings and scientific workings were displayed as part of the *Endo / Exo* exhibition in the Parsons building in 2014 (Fig. 2, 3).

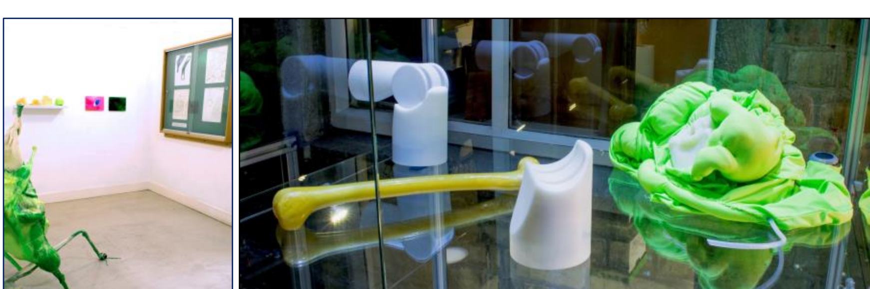

Figure 2. (Left) Exhibition view, wax exoskeleton pieces, back wall on the left. (Right) Glass cabinet, exoskeleton joints and sculpture.

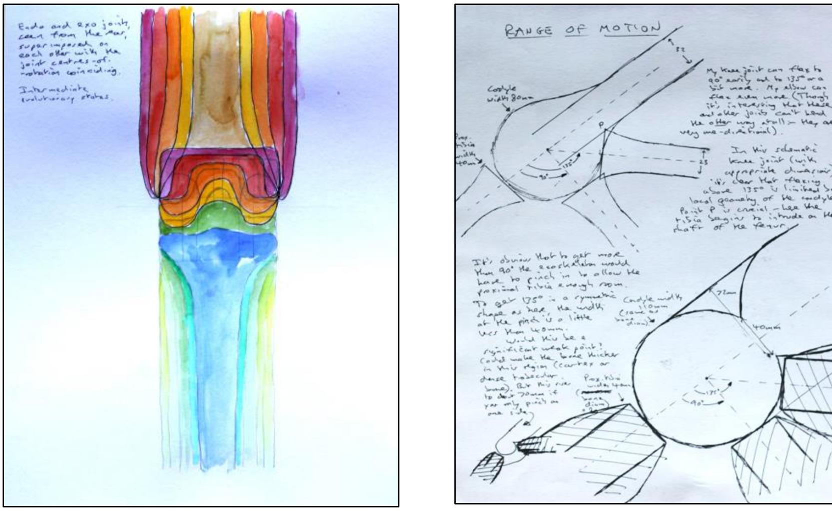

Figure 3. (Left) Evolution of the human skeleton, watercolour by David Taylor. (Right) Scientific notes and drawings in pencil by David Taylor.

2.3 *The Process Room*, Riverbank Arts Centre, 2013

The complete 3D printed exoskeleton created by David Taylor was exhibited alongside some of the scientific data and research from the exoskeleton project as part of Olivia Hassett's *The Process Room* exhibition (Fig. 4).

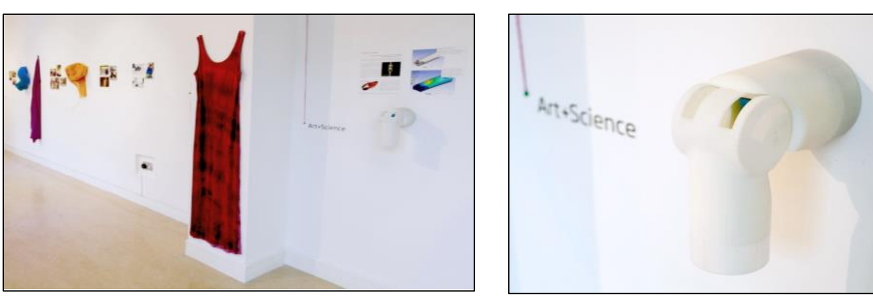

Figure 4. (Left) Exhibition view. (Right) 3D print exoskeleton by David Taylor.

2.4 *In between*, deAppendix, 2014

Our collaboration also inspired me to create a series of wax sculptures for the *In between* exhibition held in deAppendix, a hybrid art/ GP practice in Dublin. Using different mixtures of hardened wax enabled the artwork to morph and collapse in different ways over the course of the exhibition. This reflected our common interest in notions of evolution and the fragility of the human body (Fig. 5).

David and I also gave a talk on our collaboration with Dr. Ciara McMahon as part of a series of talks supporting the exhibition (Fig. 6).

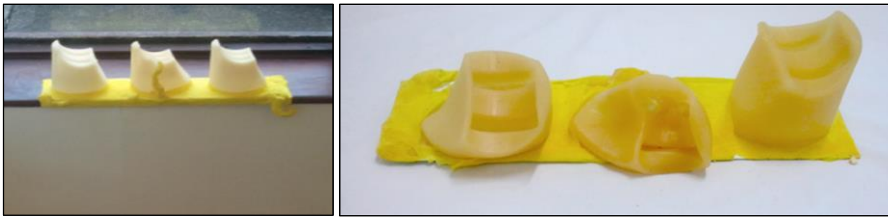

Figure 5. Wax exoskeleton piece at beginning and end of exhibition.

Figure 6. David Taylor and Olivia Hassett in conversation, deAppendix.

3. TRINITY COLLEGE TREES COLLABORATIVE PROJECT 2016/17

3.1 Laying the groundwork for the 2016/17 project.

David and I met soon after the *Endo/ Exo* exhibition to talk about what other areas of intersecting interest we might explore. For our next project we decided we wanted to engage directly with something on the TCD campus. Immediately we thought of the variety of majestic trees that were planted throughout the main campus.

In 2015 David and I were awarded a visual and performing art grant from TCD to collaborate on an art and science project about the trees of TCD. The outcomes from this project were to be displayed as part of an exhibition at the end of the project. This ended up occurring in 2017.

Our knowledge of the trees was limited so David initiated and set up a meeting with David Hackett TCD's expert grounds keeper and arboreal specialist. As David Taylor and I explained our interest in the structural and internal microscopic workings of the trees to David Hackett, pointed us in the direction of eight specific trees on the main TCD campus.

Over the following months David Taylor worked closely with Clodagh Dooley from the Advanced Microscopy Lab to create the most wonderful Scanning Electron Microscope (SEM) imagery of the various internal workings of the eight trees we were investigating (Fig. 7). The imagery created were both beautiful and inspiring.

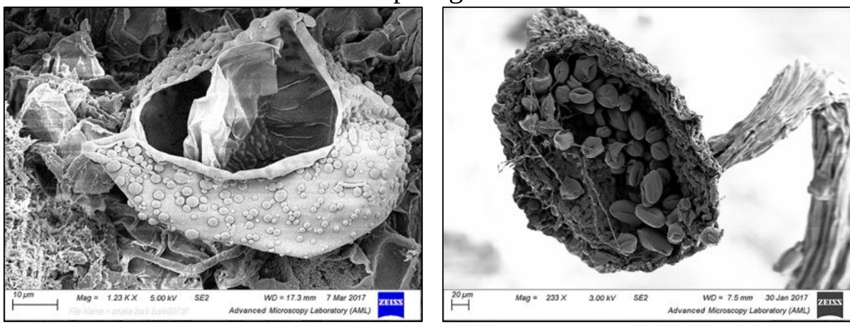

Figure 7. (Left) SEM image from Snake Bark tree. (Right) SEM image from Cherry Blossom tree.

3.2 The Trinity College Trees Exhibition, TCD, 2017

Inspired by the microscopic imagery, scientific research, physiology, and history of the tress I created eight unique artworks. These pieces were installed in the tree they were inspired by and were part of the Trinity College Trees exhibition, which ran in September/ October 2017 (Fig. 8). The eight trees involved were an Oregon Maple, a Snake bark, Hop hornbeam, Plane, Cherry blossom, Crab Apple and Yew tree.

Figure 8. (Left) Detail of Cherry Blossom artwork. (Right) Hop hornbeam artwork.

Figure 9. Pictured in front of the Oregon Maple artwork. From left to right: Clodagh Dooley, David Hackett, Olivia Hassett and David Taylor

The opening of the Trinity College Trees exhibition was part of PROBE, the European Researchers night event. I created a live art performance with the Oregon Maple tree in Library square and David Taylor led a well-received public tour of the artworks and the inspiration behind their creation (Fig. 9).

David Taylor, David Hackett, Clodagh Dooley, and I talked about the collaborative project and exhibition as part of 'Mooney goes wild' on RTE Radio 1. The progress of the Trinity College Trees project, its scientific and artistic developments and exhibition was documented on an online blog entitled Trinity College Trees [2].

4. TRINITY COLLEGE TREES COLLABORATIVE PROJECT 2018/19

4.1 Building on the scientific and artistic explorations to explore and develop a new collaborative project

Following conversations about the success of the 2016/17 TCD trees project and exhibition led David Taylor, David Hackett, and I to research and develop another proposal and apply again for a visual and performing arts grant from TCD. This time we decided we wanted to build on the scientific and artistic investigation of one of the Oregon Maple trees already undertaken in the 2016/17 project and include the other Oregon Maple in Library square.

Figure 10. (Left) One of the majestic Oregon Maple trees, Library square, 2018. (Right) Detail of artwork installation in the Oregon Maple, 2017.

The Oregon Maple artwork created in 2017 drew inspiration from the cable bracing system of high tensile steel wires that crisscrossed between the tree branches weakened over years of growth. The tendon like artwork with the cellular structure of the twigs printed onto its surface, mirrored sections of the tree bracing system (Fig. 10).

David approached Colin Reid of the Centre for Microscopy and Analysis in TCD to explore in microscopic detail a selection of samples from the second Oregon Maple in Library Square. To help us understand more about the internal fragility of these trees David Hackett also showed us detailed surveys and echoes of the internal hollow areas of the tree trunk (Fig. 11).

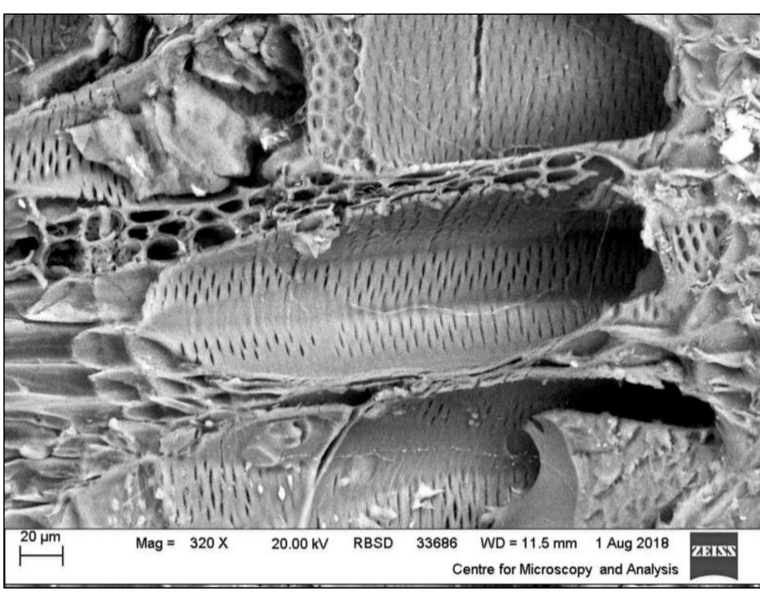

Figure 11. SEM image, section of twig transport tubes, Oregon Maple child, Parsons Building, 2019.

4.2 Reviewing and redirecting the collaborative focus

Planted in 1840 the Oregon Maple tree which we exhibited in during 2017 collapsed on June 1st 2018. As both trees were approximately 175 years old the second sister tree in Library square had to undergo immediate investigation to see if it was safe. After a few days and many tests later, on July 6th the last great Oregon Maple tree was cut down.

The focus of our project had vanished, and it seemed at the time that the project was no longer viable. The Trinity College Trees team met again to discuss what had happened and how we could redirect the project. Interesting results from the research on why the tress were so fragile and no longer able to support themselves showed much larger hollow areas in the trunk than was exposed during a survey in 2018. The lack of water due to a very hot summer and dry winter were also some of the key findings.

We were fascinated by this information and wanted to explore it further. In addition, we also decided to include another of TCD's Oregon Maple trees into the revised project. Very interestingly this tree was a child of the fallen trees and had specifically incorporated into the design and build of the 1996 extension to TCD's Parsons Building (Fig. 12). Thankfully the Provosts office understood the difficulties that we had encountered and allowed us extra time to reconfigure the project and explore the new research areas.

Figure 12. Parsons Building, TCD, 1996 extension with Oregon Maple.

4.3 Building on the scientific research. David Taylor and Tim Hone work together on various scientific research and experiments.

David Taylor and Tim Hone's work for this project involved a combination of three elements: field measurements; electron microscopy and computer simulations. The overall aim was to develop a method to assess the integrity of the trees on the Trinity College Campus and elsewhere, as regards their tendency to fail as a result of internal rot causing hollowness.

They took small pieces of the Oregon Maple wood to Colin Reid to explore the microscopic structure of the wood at high magnification in the scanning electron microscope. Alongside references to published literature, they were able to estimate its mechanical properties for input into the computer simulations.

Finite Element Analysis computer simulations with modification to the theory, to allow for the varying mechanical properties of the wood inside the tree and to consider torsional modes of loading which cause the trunk to twist, were created to simulate the loading caused by a high wind, on a tree with a given degree of hollowness (Fig. 13 & 14).

One area of research David explored was the failure modes of ageing hollow trees. Mechanics theory shows that there are several possible modes of failure for a tube loaded in bending. He investigated the potential of computer simulations to predict these failure modes. The same approach could be applied to model individual trees considered to be at risk.

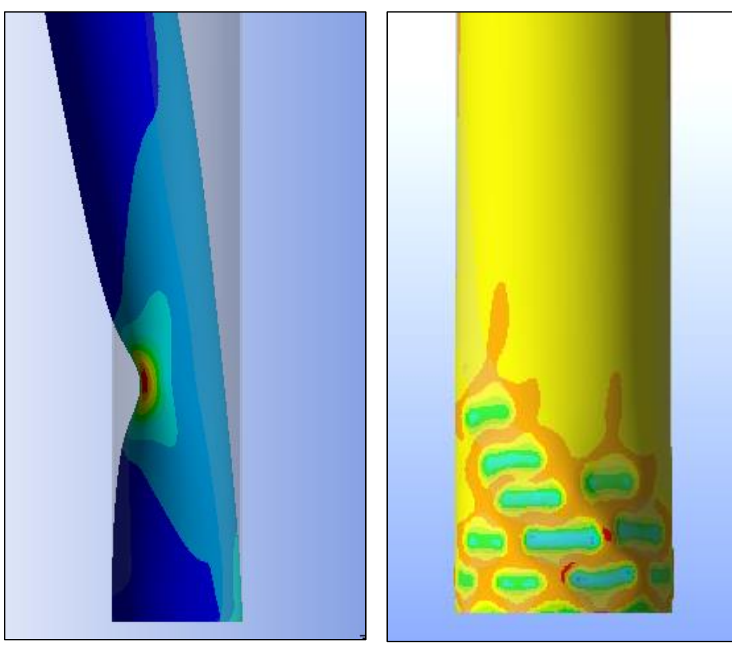

Figure 13. (Left) FEA image of ovalisation buckling left. (Right) FEA image of local buckling right.

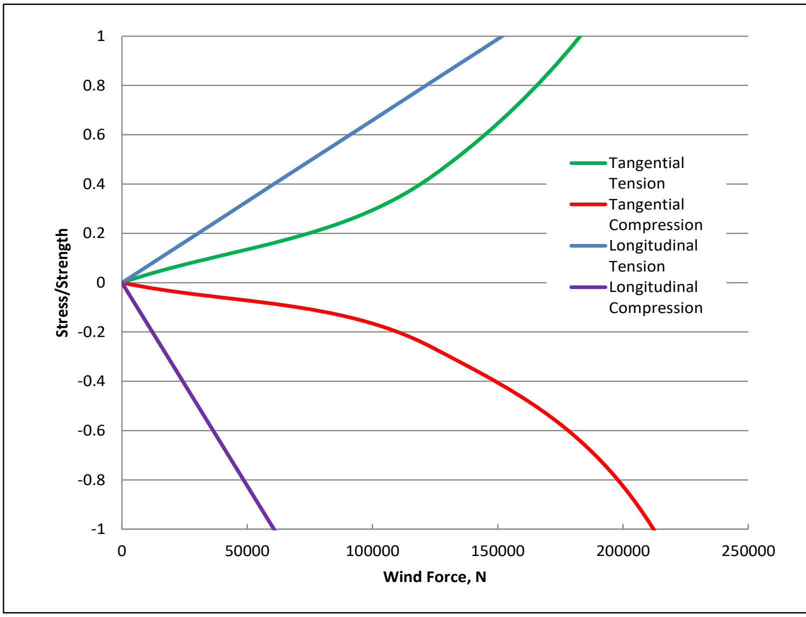

Figure 14. Failure occurs when Stress/Strength = 1, in this case by longitudinal compression at a wind force of 60,000N. The results depend on several factors: how hollow the tree is, its relative strength in different directions, etc.

Using engineering approaches, research by David Taylor and Tim Hone explored questions like how plants protect and repair themselves after being damaged. When they introduced a small crack into a plant stem and bent it to failure, it seemed much weaker as the graph below shows (Fig. 15).

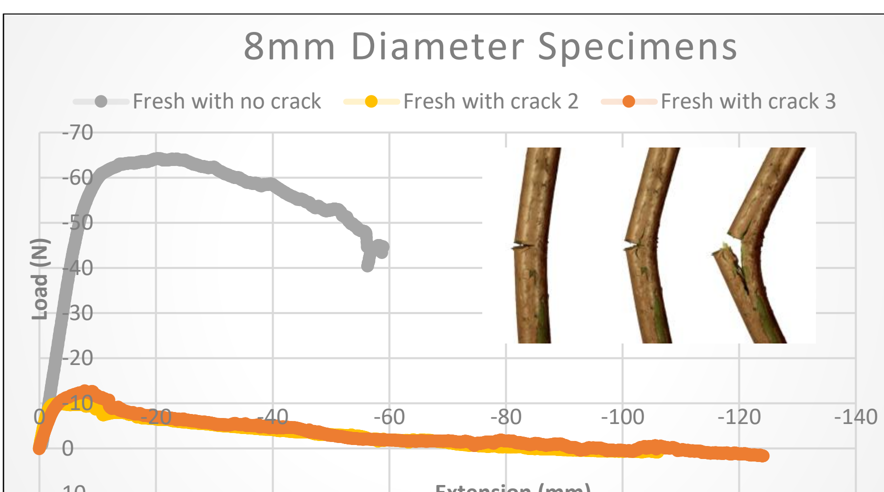

Figure 15. Load extension data for 8mm diameter plant stems and stem containing cracks.

But when they calculated the stress in the wood, the effect of the crack is much smaller as seen in Fig. 16. This showed that it is almost as tolerant of defects as steel would be under the same conditions.

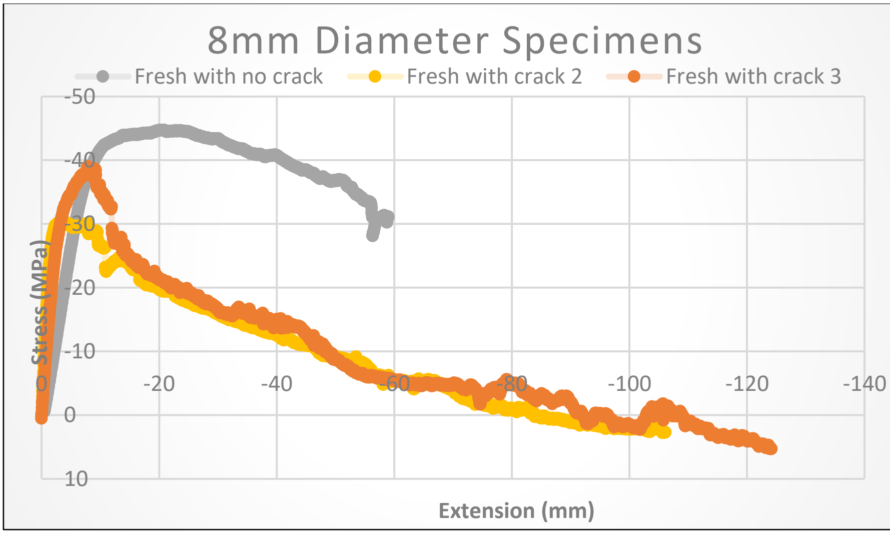

Figure 16. Stress-strain data for 8mm diameter plant stems and stem containing cracks.

4.4 TCD tree exhibition, *Embrittled* | *Resilient*, April/ May 2019

The wealth of scientific and arboreal research inspired me to create a series of new artworks. Outcomes from all the collaborators were exhibited in the Embrittled/ Resilient exhibition in April and May 2019. Located both inside the Museum Building and inside and outside the Parsons building the exhibition comprised of a mixture of artworks, scientific research, and information about the conservation of the Oregon Maple trees.

During the opening night David Taylor, David Hackett and Tim Hone introduced some of the scientific and conservation research on display in the Museum building. The collaboration and exhibition were again added to the Trinity College Trees online blog (2) and covered on the Mooney goes Wild programme on Radio 1 on April 8th, 2019 (Fig. 17).

Figure 17. Display in Museum building of David Taylor and Tim Hone's scientific research.

Outcomes displayed in the Parsons building included research by David Taylor on the failure of hollow tubes in bending (Fig. 18).

Figure 18. Display in the Parson's Building of David Taylor's research on the bending and failure of hollow tubes.

The outdoor exhibit was inspired by and installed around the Oregon Maple child tree embedded in the Parsons building. Modelled on scanning electron microscope images taken by Colin Reid of the microscopic tubes that carries the water and nutrients up the Oregon Maple I created a series of tube-like sculptures to encircle the tree.

Each of the sculptures comprised of laminated layers of various images printed onto paper from the numerous scientific studies undertaken by David Taylor and Tim Hone, and a layer of macerated plant material saved from the fallen trees, which were embedded under layers of acid free tissue. Finally, the sculptures were coated with a unique bio plastic protective layer developed in conjunction with Conor Buckley.

In a similar vein to the wax exoskeleton pieces developed at the beginning of our collaborative process the materials choice was a deliberate one. The installation was designed to alter and change in response to the environmental factors exerted on them throughout the duration of the exhibition. In fact, each tube buckled, bent, and collapsed in different ways mirroring the imagery and elements of David Taylors research (Fig. 19).


Figure 19. View of sculptural installation with Oregon Maple, April-May 2019

5. CONCLUDING REMARKS

I feel very privileged and grateful to have explored common interests and created numerous well-received exhibits with David Taylor over the seven years of our collaboration. The highlight for me was the positive response of TCD's staff, students, and the public to the extensive research we undertook and the outcomes of the two Trinity Trees projects. Working with David has deepened and enhanced my own practice leading to new and surprising avenues of research. I wish David continued joy exploring his interest in the overlaps between science and art.

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INDEX

Perspectives on the Mechanics of Fracture and Biological Materials presents a set of essays in honour of David Taylor, Engineer and Educator at Trinity College Dublin. The essays are contributed by colleagues, collaborators, and former students of David Taylor. Topics include fracture mechanics, biomechanics, and forensic engineering in which a range of engineering and biological materials including metals, polymers, bone, and insect exoskeletons are discussed. The unifying theme among of all these topics is fracture, a phenomenon David has spent his career studying. Yet despite his fascination with things breaking apart, throughout his career he has been instrumental in bringing people together for the better of his students, his university, to the engineering discipline as a whole, and more recently to the arts. The extensive and diverse range of topics discussed in this book reflects the substantial contribution of David Taylor, and to the impact he has had on so many.

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ISBN 978-1-4716-1942-7