Institution:
University of Cambridge

Unit of Assessment:
UoA15

Title of case study:
Lattice Sandwich Structures for Ships

Summary of the impact (indicative maximum 100 words)
Research at University of Cambridge Department of Engineering (DoEng) has created a new fundamental understanding of the static, dynamic and blast performance of lattice sandwich structures (a repeating pattern of metal struts between two sheets of metal). Ship builders in the Netherlands and the USA have built over 19 ships worth approximately GB200M using this technology since 1/1/2008 with many more planned. These ships are:

- less likely to rupture in low speed collisions, which is important especially for river tankers
- compliant with new standards for the carriage of dangerous goods by inland waterways in Europe at a lower cost, because the designs are simplified
- blast resistant, which is important when considering potential terrorist threats.

2. Underpinning research (indicative maximum 500 words)
Research by Norman Fleck (appointed as Lecturer in DoEng in 1985 and promoted to Professor in 1997) and Vikram Deshpande (appointed as Assistant Lecturer in DoEng in 2000, promoted to Lecturer in 2003 and promoted to Professor in 2010) sought to address industry's need for lightweight, stiff, blast resistant sheets. The research was conducted in three main phases:

1. Metal foams, which formed a foundation for the next phase (1996-2005)
2. Blast-resistant materials, which produced results that were directly applied to the blast-resistance of sandwich structures and ship hulls (2001-2013)
3. Lattice sandwich structures, which produced results that were directly applied to the design and optimisation of sandwich structures and ship hulls (2003-2013).

Phase 1 – Metal foams (1996-2005)
The research to understand the performance of metal foams was in collaboration with Mike Ashby (appointed as Professor in DoEng in 1973, retired from DoEng in 2001, and Category C in DoEng for RAE2008). The work included sandwich structures in which the metal foams were clad by two sheets of metal to create a low density, stiff material that can absorb impacts without rupturing. The research was funded by a series of US Navy and Office of Naval Research (ONR) grants that provided over GBP650k of funding. Constitutive models for metal foams were a key research output (Ref 1).The research outputs were captured in a book that has sold over 2000 copies (Ref 2).

Phase 2 – Blast resistant materials (2001-2013)
Blast resistance was researched by Fleck and Deshpande with grants from DARPA and ONR with top-ups from the Isaac Newton Trust. These grants totalled more than GBP1.5M. Fleck and Deshpande combined molecular dynamics codes with finite element analysis to enable discrete particle prediction of the blast and ballistic responses of foam and lattice sandwich structures (Ref 3). Their major contribution to the field was a method for analysing the full structure under high-speed deformation and the validation of this method through experiments using foam projectiles (Ref 4) and an instrumented water tube. The work was extended to include ballistic responses.
Throughout the work on metal foams and lattice materials, Fleck and Deshpande collaborated with: John Hutchison of Harvard University, and Tony Evans and Bob McMeeking of University College Santa Barbara on theory. These collaborators focussed on a continuum mechanics approach which aimed to simplify modelling by defining the properties of a homogeneous core that would give approximately the same response as the real lattice structure. This approach developed the overall scientific understanding of lattice sandwich structures, but it was Fleck and Deshpande's work on analysing the full lattice using finite element modelling that enabled the design and optimisation for practical full-scale applications.

Phase 3 – Lattice sandwich structures (2003-2013)

Independently of this research, Y-core lattice sandwich structures for ship hulls were invented and patented by Damen Schelde Naval Shipbuilding (DSNS), a shipbuilding firm based in the Netherlands, in 1998. While the structure showed performance advantages versus traditional materials in terms of stiffness and toughness, DSNS had only an empirical understanding of how to tune the structure to control its properties, which made optimisation impossible given the cost of large-scale empirical tests on hulls.

In 2003, the research at DoEng and the invention at DSNS came together. DSNS went through the Netherlands Institute for Metals Research (NIMR – subsequently known as the Materials Innovation Institute) to gain matching government funding to place research grants with Fleck and Deshpande at DoEng to understand, model and optimise the Y-core lattice material. Two consecutive grants resulted which created a method to optimise the design of Y-core sandwich structures (2003-2011).

In parallel, Fleck and Deshpande won funding from other sponsors to build on this research with DSNS to investigate not only DSNS' Y-core lattice structures, but also the US Navy's competing sandwich structure (Nav-Trus) that used a corrugated core. The grants were funded by the EC, EPSRC and DARPA, and with the NIMR grants, totalled more than GBP980k.

As results of the research described above, Fleck and Deshpande:

- established methods for making small-scale Y-core (and Nav-Trus) samples and testing these samples under static and dynamic loading conditions (Ref 5)
- created new finite element modelling techniques to enable the performance of full-scale ship hulls to be accurately predicted from these small-scale tests (Ref 5)
- devised an approach for optimising Y-core, Nav-Trus and other lattice materials (Ref 6).

The experimental work included creating a test rig for a 1000kN servo-hydraulic machine to apply cyclic fatigue loads to prototypes. A 10W continuous laser was used to illuminate the structure for high-speed Moire shadow interferometry.

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

1*. Deshpande, V.S. and Fleck, N.A. (2000). Isotropic constitutive models for metallic foams. J. Mech. Phys. Solids, 48 (6-7), pp 1253-1283, DOI: 10.1016/S0022-5096(99)00082-4.

2. "Metal Foams: A Design Guide". Ashby, M.F., Evans, A., Fleck, N.A., Gibson, L.J., Hutchinson, J.W. and Wadley, H.N.G. (July 2000). Butterworth-Heinemann, ISBN-10: 0-7506-7219-6 (available from DoEng).

3*. Liu, T., Fleck, N.A., Wadley, H.N.G. and Deshpande, V.S. (2013). The impact of sand slugs against beams and plates: Coupled discrete particle/finite element simulations. J. Mech. Phys. Solids, 61 (8), pp1798-1821, DOI: 10.1016/j.jmps.2013.03.008.

4*. Radford, D.D., Deshpande, V.S., and Fleck, N.A. (2005). The use of metal foam projectiles to simulate impulse loading on a structure, J. Impact Engineering, 31, pp1152-1171, DOI: 10.1016/j.ijimpeng.2004.07.012.

5. Rubino, V., Deshpande, V.S., and Fleck, N.A. (2008). The dynamic response of end-clamped sandwich beams with a Y-frame or corrugated core, Int. J. Impact Engineering, 35 (8), pp 829-844, DOI: 10.1016/j.ijimpeng.2007.10.006.

6. Pedersen, C.B.W., Deshpande, V.S. and Fleck, N.A. (2006). Compressive response of the Y-shaped sandwich core, European J. Mechanics, A, 25 (1), pp125-141, DOI: 10.1016/j.euromechsol.2005.06.001.

*Best represent the quality of the research.

The quality of the research is demonstrated not only by the research outputs themselves but by the fact that: Fleck delivered the GI Taylor Lecture at the Cambridge Philosophical Society entitled "Microarchitectural cellular solids - from blast-resistant ships to shape-changing wings" in 2005; Fleck won the Humboldt Award in 2011; Fleck won the ASME Koiter Medal in 2013; and Deshpande was promoted to Professor in 2010.

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

The impact of the research is described in two statements below. The first, from DSNS, explains how many commercial ships have been built using the DoEng research outputs, how much they are worth, why the DoEng research outputs were important and how this work has changed mindsets across the shipbuilding industry. These impacts can be presented openly. The second statement is from the US Defence Science Research Council and it explains the importance of the DoEng research in providing protection against terrorist attacks, how DoEng results led to the formation of a company to produce the materials for large-scale roll-out, and how international governments are cooperating to exploit this new technology. Unfortunately, it is not possible to provide details because they are secret and cannot be released even under confidential covers.

1. The Research Coordinator of DSNS, states: *"While we held the patent for Y-core lattice sandwich structures, we did not have the fundamental understanding and related tools to make efficient use of our invention. Our investment in research at the Department of Engineering in Cambridge generated results that enable us to design and build ships using Y-core lattices. We have sold patent licences for 19 ships from 2008 to 2013 with 2 more on the drawing table, at an average of selling price of approximately EUR10M per ship. These ships are worth nearly EUR200M in total, and include the world's largest (Ms. Vorstenbosch) and the world's most environmentally friendly chemical tankers (Ms. Argonon sailing on LNG). All of these ships are river tankers sailing through densely populated areas with dangerous cargo onboard. The hulls do not rupture if there are low-speed collisions and offer enhanced protection compared to conventional ship structures. Together with TNO, the Dutch Centre of applied science new regulation has been developed adopting a risk based design approach (Ref. European Agreement concerning the international carriage of dangerous goods by inland waterways (ADN 2009 Vol.1 United nations). This allows ship owners to apply larger tank sizes without increasing the risk of a cargo spill by adopting energy absorbing structures like the Y-core innovation. Larger tank sizes imply less tanks in the same ship hull resulting in less pumping and piping equipment and faster loading and unloading which offers, apart from enhanced safety, also an economic advantage to ship owners. The latest research also shows that they are resistant to blast, which is becoming an increasing issue with regard to terrorism. Our mindset and the mindsets of our customers has changed greatly with the introduction of this technology and we expect more tankers to be built this way in the future."*

2. In the USA, the US Navy has transitioned sandwich panel designs into blast-resistant ships, in an USD10M programme. A University Professor at the University of Virginia and long-term member of the Defense Science Research Council, states that: *"The research by Norman Fleck and Vikram Deshpande at the Department of Engineering at Cambridge has addressed a key concern arising from the terrorist attack on the USS Cole in 2000. In this attack, the blast from an unsophisticated bomb delivered by a small boat, ruptured the destroyer's hull. The outputs of Fleck and Deshpande's work have enabled design and optimization of lattice sandwich structures for ship hulls, so that they can now resist such attacks. These new structures also enable mitigation of the damage caused by explosions in air and from buried mines. In these latter cases, the Cambridge group made pivotal discoveries that helped focus the US research onto the right physical mechanisms, and thus the best approach to maximize the considerable benefit of sandwich constructions. US Company, Cellular Materials International Inc was formed in 2001 to capitalize on these discoveries, and is deeply involved in rolling-out large scale solutions to blast problems. The Technical Cooperation Program (TTCP) – an international organization that facilitates cooperation between the governments of Australia, Canada, New Zealand, the UK and USA – has also recognized the importance of the Cambridge work in blast mitigation, and has established a significant multinational program to investigate its applications with the member nations."*

In addition to the impacts described in the two statements above, the DoEng constitutive model for metal foams has been embedded in Abaqus finite element analysis software since 2000. It is the basis of the software's crushable foam plasticity model. Abaqus is one of the market leaders in the field of finite element analysis with more than 30,000 users worldwide.

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

1. Statement received from Research Coordinator, DSNS.
2. Statement received from University Professor at the University of Virginia and long-term member of the Defense Science Research Council.
3. The Founder (in 1978) and Chairman of ABAQUS Incorporated, which became Simulia Incorporated, a wholly-owned subsidiary of Dassault Systèmes, in 2005, can corroborate statements concerning Abaqus software.