Institution: University of Strathclyde

Unit of Assessment: 12

Title of case study: Guidelines and standards which improve design and safety of marine structures subject to steep wave impact

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

Guidelines and standards underpinned by Strathclyde research have improved the design, assessment and the safety of marine structures subjected to wave impact in large steep waves. The guidelines and standards are widely used in the design of floating structures, particularly Floating Production, Storage and Offloading vessels (*FPSO*s) and offshore wind turbines. Since January 2008 the work has impacted the design, strength assessment and failure analysis of fixed offshore oil and gas platforms, renewable energy devices and ships. The guidelines and standards are used by designers to mitigate against damage caused by breaking wave impact, thereby improving the safety of mariners and offshore workers, reducing lost production due to downtime, and cutting the risk of environmental impact due to oil pollution. The research has also been used by Strathclyde researchers in industry-focussed studies, in legal work related to the loss of the oil tanker Prestige (2009-2013), in the assessment of the Schiehallion FPSO for BP (2010), and design of a Scottish harbour wave screen (2009) that allows ferries to access and stay in the harbour in more severe weather.

2. Underpinning research (indicative maximum 500 words)

Context:

The research began when three inter-related collaborative proposals were awarded by EPSRC (1999-2002) to Barltrop and Huang, Incecik, and Vassalos and Turan to investigate the response of Floating Production, Storage and Offloading vessels (FPSOs) in extreme conditions. The proposals were triggered by Barltrop' s observation that Health and Safety Executive (HSE) 'guidance notes', he had written previously for offshore structures, needed further research in order to properly address wave impact. The FPSO *Schiehallion* was proposed as a test case, as it had been damaged in 1999 by wave impact in severe conditions, confirming that existing approaches to design and construction of FPSOs and estimation of wave loading were inadequate.

Key findings:

An extended program of research was subsequently performed for BP which continued from 2001 to 2003 under the EU *SAFEFLOW* project in parallel with the Industry-funded *FLOW* Joint Industry Project and PhD research. Barltrop supervised research on instrumented three-metre models of the curved bow *Schiehallion* and conventional tanker *Loch Rannoch* that were tested in the Kelvin Hydrodynamics Laboratory with all data analysed by Strathclyde. In parallel, a flat bow was tested in a large test tank operated by MARIN (Maritime Research Institute Netherlands), with data analysis carried out by researchers from Strathclyde and Atkins. The Strathclyde study was validated by comparison with full scale data obtained from *Schiehallion*.

Further insight into the importance of reflected waves on impact loads was gained through a research study undertaken in conjunction with the University of Glasgow in 2004-2005 on the effect of large waves impacting Shetland cliffs. A subsequent CFD study (2005-2009) investigated the nature of deep-water breaking waves, vessel motions, global loads on hull structures, and local pressure loads caused by extreme wave impact events.

A further programme of CFD and acoustic-based research was funded between 2009 and 2013 by insurance companies, via lawyers, addressing the loss of the tanker "MV Prestige" as a result of a breaking wave impact. The Prestige sank in 2002 causing extensive pollution, especially to Spain's NW coast. This work considered side impact and the effect of air in water on impact pressures. Related studies using the techniques developed have been carried out by Barltrop, Huang and Incecik (2000-2004) on wave impact loading on wind turbine structures, funded by EPSRC (2000-2004), and on ship side impact by Day and Barltrop (2010-2012).

The key findings of the research all relate to the development of better insight into the phenomena related to wave impact on floating structures. In particular the findings lead to improved understanding of the probability of extreme wave impact (Section 3: Reference 1and 2, G1, G4), the types of wave leading to the greatest loads (Reference 1 and 3, G1), the effect of detailed hydrodynamics (including surface tension and aeration) on wave impact loading (Reference 3), the significance of the role of wave reflection in loading (Reference 4) the importance of added mass effects in the fluid-structure interaction (G4), the importance of “green water on deck” phenomena (G4), and the effect of water depth (G3).

The research also led to development of simplified equations and time domain simulations for impact pressures suitable for use in design, and improved estimates for safety factors for 100-year return period wave impacts (Reference 2, G1, G4)

Key Researchers at Strathclyde
The key researchers were employed in the Dept. of Naval Architecture and Marine Engineering at the time of the research. Prof N Barltrop (1999-2013); Prof D Vassalos (1999-2002); Prof O Turan (1999-2002); Prof Huang (2001-04); Prof A Day (2010-12); Prof A Incecik (2011-2012).

3. References to the research (indicative maximum of six references)
References 1, 2 & 3 best indicate the quality of the research

1. Xu L., Barltrop N. and Okan B. (2008) “Bow impact loading on FPSOs 1 - experimental investigation” Ocean Eng. Vol 35, No 11-12, pp1148 - 1157 http://dx.doi.org/10.1016/j.oceaneng.2008.04.013

2. Xu L. and Barltrop N., (2008) Bow impact loading on FPSOs 2 - theoretical investigation, Ocean Engineering Vol 35, No. 11-12, pp1158-1165 http://dx.doi.org/10.1016/j.oceaneng.2008.04.012

3. Ojieh, N., Barltrop, N. and Xu, L. (2009), RANS investigation of the kinematics of an alternative extreme wave,Ocean Engineering, 36 (17-18), pp1415-1424, http://dx.doi.org/10.1016/j.oceaneng.2009.08.009

4. Hansom J., Barltrop N. and Hall A., (2008) Modelling the processes of cliff-top erosion and deposition under extreme storm waves, Marine Geology Vol 253, pp. 36-50 http://dx.doi.org/10.1016/j.margeo.2008.02.015

Other evidence for research quality
Key research was supported by the following EPSRC funded projects

G1 GR/M62525/01 *COMPARISON OF MODEL TESTS & FULL SCALE DATA WITH THEORY;* PI Barltrop, Professor N. Oct 1999-Dec 2002. £86k

G2 GR/M62501/01 *FPSO SAFETY IN EXTREME ENVIRONMENTS* PI Vassalos, Professor D, Oct 1999-Dec 2002. £42k

G3 GR/N04539/01 *DYNAMIC RESPONSE OF WIND TURBINE STRUCTURE IN WAVES* PI Barltrop, Professor N., Co-I Huang, Dr S. Oct 2000-June 2004. £141k

G1 & G2 were supported by W.S Atkins, BP, Lloyds Register, Shell, Harland & Wolff and Technip.

EU SAFEFLOW & Flow JIP (Joint Industry Project)
G4 Prof Bas Buchner (Scientific Co-ordinator), MARIN, Haagsteeg 2, PO Box 28, NL-6700 AA Wageningen; Jan 2001 – Dec 2003, sponsors/partners: Regulators: ABS, Bureau Veritas, DNV, HSE, NPD; Industry: Amerada Hess, Astano/Izar, Atkins, Bluewater, BP, Chevron, Conoco, Daewoo, FMC Sofec, IHC Gusto/SBM, Norsk Hydro, Offshore Design, PAFA, Phillips Petroleum, Shell, Statoil, Texaco; Universities: IST-Lisbon, University of Groningen.

4. Details of the impact (indicative maximum 750 words)
Process from Research to Impact:
The key process through which the research generated impact was the development of guidelines and standards used in the maritime industries to design vessels/structures with improved resistance to wave impact loading and thus improved safety and economics**.** Results and

recommendations from the laboratory studies on wave impact were published as guidance by HSE in 2005 (*Wave Slap Loading on FPSO Bows, Source 6)*. The results from the *SAFEFLOW* and *FLOW JIP* projects were published as *Summary Report on Design Guidance and Assessment Methodologies for Wave Slam and Green Water Impact Loading* (Source 7). These documents are still the most detailed and up to date guidance for the design of Floating Offshore Platforms against wave impact. The guidance covers wave loading on the hull, deck and deck mounted equipment. Whilst Safety Cases for offshore platforms in the UK sector of the North Sea are not based on mandatory guidance, industry would be expected by the regulators to refer to the HSE and SafeFlow guidance. The two guidance documents underpinned by Strathclyde research have been used to design (or redesign) offshore structures to ensure safe operation, thus reducing the risks to the vessel crew, and the risks of oil spillage to the environment, and loss of oil supply to the public, whilst reducing economic losses to oil producers.

The Strathclyde research on waves and wave impact has directly informed the oil industry and regulator sponsors; furthermore, through Barltrop's membership of the standards committees has informed the ISO standards (*19904-1 Floating Offshore Structures* (Source 8),*19902 Fixed Steel Offshore Structures* (Source 9) for offshore oil and gas platforms. Barltrop also contributed to the International Electrotechnical Commission IEC TC 88, which developed IEC/BS standard *61400-3 Wind turbines - Part 3: Design requirements for offshore wind turbines* (Source 10) incorporating guidance on wave loading, published in **2009.** Barltrop is currently working on the revision of both the ISO and IEC documents, providing essential reference for the safe design of fixed and floating offshore structures in the fields of oil, gas and wind energy.

Impact on Marine and Offshore Design and Safety:
In **2010** the *Schiehallion* FPSO bow impact loading was reassessed for BP by Atkins and Strathclyde, using the Strathclyde simple rule formulae and both the Strathclyde and Marin time domain models. This structure has subsequently operated safely until **2013** in the Schiehallion field, West of Shetland. (Source 1) The cost of the lost production due to 10 days downtime due to the damage incurred in 1999 was estimated to be about $35 million. The Strathclyde and Safeflow research has been the basis for the estimation of bow loading on the Schiehallion replacement vessel. This has been approved by BP, accounting for the HSE/Safeflow guidance and data from the Strathclyde/ Atkins **2010** wave impact studies. The replacement vessel (likely to cost in the region of $2-3 billion) is currently in-build and will be installed in **2014** (Source 1).

The series of circular FPSO vessels designed by Sevan Marine ASA Oslo, were designed according to this guidance based on input to design consultants British Maritime Technology (BMT). This series of vessels including *Hummingbird* (launched in **2008**) and *Voyager* (launched in **2009**), now owned by Teekay Shipping, are still operating. Each of these vessels are worth around $US 0.5-1 billion (Source 2).

Knowledge gained from Strathclyde research has been used by Barltrop in the assessment of safety of the structure during possible impact loading on the deck of the North Rankin-A fixed platform off Western Australia for Woodside Petroleum in **2009**. Value of the North Rankin Platform is estimated to be worth around $2-3 billion. Work by Barltrop contributed to the decision that the platform could continue to operate safely (Source 3).

In **2009** a damaged wave screen protecting the ferry berths in Kirkwall Harbour, Orkney was subsequently assessed and redesigned using results, from Barltrop based on software developed for the *SAFEFLOW* project (Source 4). The value of this wave screen installed is estimated to be £300k; its presence has both a societal and financial benefit by allowing ferry operations to access and remain in the harbour in more severe weather for about 20% more time.

The expertise has also been exploited to examine and provide guidance on wave load and wave impact for safe design of offshore wave energy devices; namely the Naval Dynamics AS device, designed in **2008** and the Aquamarine Oyster II built in **2011** and currently undergoing full scale testing at the European Marine Energy Centre (EMEC) in the UK.

Influence on legal proceedings:
The oil tanker *Prestige* sank after breaking in half in 2002 off the coast of Galicia, causing one of the most damaging oil spills in history, with a clean-up cost estimated at €2.5 billion. In October 2012 a Spanish court opened the trial of the former captain and three other defendants over their involvement in the oil spill. The main defendant is the captain of the Prestige, against whom prosecutors are seeking a 12-year prison sentence. Besides pursuing criminal charges, prosecutors are demanding financial compensation from the ship's insurers to cover the costs of the spill. The Spanish state raised its total claim to about €4.33 billion, from an initial estimate of €1.9 billion. France has so far claimed €86 million in damages.

Based on his wave impact research, Barltrop was asked to write expert reports (from 2009 to 2012) and to give expert testimony in the Spanish, Galicia Region, High Court, in 2013. In court there were two experts on hydrodynamics: Barltrop and another from Spanish Model Basin (Cehipar). Results of the Strathclyde research played an important role in explaining the nature of the waves, wave loading, structural response and the interpretation of the model test results. Of particular importance, owing to the effects of air in the water, on the basis of his research, Barltrop argued that the scaling factors applied by Cehipar were only 60% of the correct values. This evidence is highly significant as it indicates the hull strength must have been 66% higher than was implied by the Spanish tests. This indicates a properly, rather than poorly, maintained hull and this will affect the court's decision as to the cause of and responsibility for pollution and clean-up costs (Source 5). Court judgement is expected in before the end of 2013.

Wider impact:
Research impact has been through the development of guidance and standards, use of these guidance and standards by other parties, and through consultancy and expert evidence by Prof Barltrop and Prof Incecik. The guidance and standards provide better understanding and quantification of the response of the shell plating of FPSOs and conventional tankers due to wave impact loads which in turn enables the designers to manage the risk of oil pollution and possible loss of life due to shell rupture. Inevitably, we only know the detail of a small proportion of the overall application of the standards and guidance: i.e. applications in which Strathclyde researchers have had some direct involvement.

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

1: Naval Architect at British Petroleum can be contacted to support claims related to work on Schiehallion
2: Technical Manager Fluid Mechanics Limited can be contacted to support claims related to work on Hummingbird and Voyager.
3: Structural Project Engineer, Woodside Energy Ltd can be contacted to support claims related to work on North Rankin-A
4: Leader**,** Advanced Technology Team, Scott Wilson Ltd can be contacted to support claims related to work on Kirkwall Harbour:
5: Lawyer from Ince & Co LLP can be contacted to support claims related to testimony on Prestige
6: Barltrop, N.D.P. Xu, L. HSE report RR324. (2005) Available at: http://www.hse.gov.uk/research/rrhtm/rr324.htm
7: *Summary Report on Design Guidance and Assessment Methodologies for Wave Slam and Green Water Impact Loading*, Buchner, Hodgson, Voogt, Ballard, Barltrop, Falkenberg, Fyfe, Guedes Soares, Iwanowski, Kleefsman. August 2004.
8: ISO19904-1 Floating Offshore Structures, 2006, http://www.iso.org/iso/catalogue_detail.htm?csnumber=22995
9: ISO 19902 Fixed Steel Offshore Structures, 2007, http://www.iso.org/iso/catalogue_detail.htm?csnumber=27507
10: IEC/BS EN 61400-3:2009 Wind turbines - Part 3: Design requirements for offshore wind turbines http://shop.bsigroup.com/en/ProductDetail/?pid=000000000030170387