Institution: University of East Anglia		
Unit of Assessment: 10 – Mathematical Sciences		
Title of case study: Danger on the seas: Assessing the risk to ships from wave slamming events		
Period when the underpinning research was undertaken: 2008-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Alexander Korobkin	Professor in Applied Mathematics	2007 - to present
Tatyana Khabakhpasheva	Senior Research Assistant	2014 - to present
Period when the claimed impact occurred: 1st August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Large ships and offshore structures face a serious risk of damage from severe wave events in rough waters. Slamming events occur when the hull of a ship slams the water surface, or a wave slams a ship, potentially causing catastrophic damage. Bureau Veritas is an international service company with an annual turnover of around GBP5,100,000,000 and 1500 offices and labs across 140 countries that specialises in quantifying risk for seagoing vessels. Since 2007 research by Professor Korobkin, in the School of Mathematics at UEA has guided and informed the technical development in Bureau Veritas with regard to slamming events. The mathematical models developed at UEA have produced new tools and methodologies that are used by the company on a daily basis. Professor Korobkin played a vital role in the development of HOMER, the software suite that Bureau Veritas use to determine the structural response of floating units under specified wave conditions. HOMER is now used by more than 15 research and engineering institutions worldwide including shipyards.

2. Underpinning research

Simulating slamming events requires accuracy over very short timescales and across highly localised regions in space, both major challenges for Computational Fluid Dynamics (CFD) codes. Slamming models based on nonlinear potential flow theory or on the Navier-Stokes equations are computationally expensive, do not easily capture elastic deformations, and are restricted to particular conditions. These difficulties dictate the need for alternative approaches that have greater flexibility and are computationally cheaper. Over a series of research articles written at UEA, Professor Korobkin has thoroughly revised existing wave-slamming models by taking a robust, simplified approach that provides generic information of great utility and insight across a wide range of conditions and at minimal computational cost:

- In R1 he developed an accurate and robust algorithm for evaluating slamming loads in 2 dimensions.
- In R2 he presented a methodology for calculating the forces on ship-like bodies and demonstrated that they are highly accurate and are consistent with CFD computations.
- In R3 (with Dr. S. Malenica from Bureau Veritas) he presented a hydroelastic model of slamming for complicated structures.
- In R4 he developed a new model of water exit and justified its practical importance. He demonstrated that, surprisingly, exit loads can be even larger in magnitude than entry loads.
- In R5 he presented a methodology for handling hydro-structure interactions that is now used in industry.

Professor Korobkin introduced a displacement potential for slamming problems and reformulated these problems as variational inequalities. This approach is now widely adopted and has led to improved, more accurate and efficient algorithms for estimating the stresses in elastic structures, such as seagoing vessels, that are subject to slamming loads. It is the only semi-analytical approach that can handle three-dimensional slamming problems. This new approach also allows for the approximation of loads on a ship section exiting from water and, importantly, is much better suited to a reliable statistical analysis than CFD modelling, therefore providing an attractive theoretical framework for analysing ship slamming in realistic sea conditions.

The power of Professor Korobkin's new ideas is illustrated by the Joint Industrial Project "Sloshel" (R5). This project examined hydro-structure sloshing interactions in the tanks of Membrane Type Liquefied Natural Gas Carriers - an extremely challenging problem. Traditional small-model tests suffer from scale effects and there are numerous issues with direct CFD calculations not least the prohibitive computational cost. The mathematical models developed by Professor Korobkin were combined with numerical finite-element codes in a semi-analytical approach to successfully capture the structural response of the real (full scale) containment system under breaking wave impacts. Importantly, the key physical effects of hydroelasticity, mixing between the liquefied natural gas and its vapour, and fluid compressibility were introduced into the model thereby improving the veracity of the simulations.

3. References to the research

Underpinning research

The underpinning research outputs have all been published in competitive, international, peer-reviewed journals and form part of a larger body of such published work. Citation numbers are from Google Scholar.

(UEA authors in **bold**)

R1 Generalised Wagner model of water impact by numerical conformal mapping
Khabakhpasheva, T. I., Kim, Y., & **Korobkin, A. A.**
Applied Ocean Research, **2014**, 44, 29-38.
DOI: 10.1016/j.apor.2013.10.007
Citation count = 34

R2 Two-dimensional water entry and exit of a body whose shape varies in time
Tassin, A., Piro, D. J., **Korobkin, A. A.**, Maki, K. J., & **Cooker, M. J**.
Journal of Fluids and Structures, **2013** 40, pp. 317-336.
DOI: 10.1016/j.jfluidstructs.2013.05.002
Citation count = 77

R3 Maximum stress of stiff elastic plate in uniform flow and due to jet impact
Korobkin, A. A., Khabakhpasheva, T. I., & Malenica, S.
Physics of Fluids, **2017**, 29(7), 072105. DOI: 10.1063/1.4990974
Citation count = 5

R4 Hydrodynamic forces in water exit problems
Korobkin, A. A., Khabakpasheva, T. I., & Maki, K. J.
Journal of Fluids and Structures, **2017**, 69, 16-33.
DOI: 10.1016/j.jfluidstructs.2016.12.002.
Citation count = 9

R5 Combined Semi-analytical and Finite Element Approach for Hydro Structure Interactions during Sloshing Impacts – "Sloshel Project"
Malenica, S., **Korobkin, A. A.,** Ten, I., Gazzola, T., Mravak, Z., De-Lauzon, J. & Scolan, Y. M.
Proceedings of the Nineteenth International Offshore and Polar Engineering Conference, Osaka, Japan, June 21-26, **2009.** ISBN: 978-1-880653-53-1
Citation count = 8

Underpinning funding

"Tools for Ultra Large Container Ships" (TULCS)
PI: **Korobkin, A**.
Funder: CEC + BUREAU VERITAS SA

Total project value EUR3,850,000 (UEA value GBP86,645)
Dates: 1/06/09 → 30/11/12

NICOP project "Fundamental Analysis of the Water Exit Problem"
PI: **Korobkin, A**.
Funder: US Office of Naval Research.
Grant value: GBP170,143
Dates: 15/09/13 → 30/09/16

4. Details of the impact

Figure 1: Damage to the Hull of MSC Napoli.
Picture Reproduced courtesy of Marine Nationale.

The safe operation of ships is of high priority in order to protect the ship, the personnel, the cargo and the wider environment. Ships and offshore structures, such as rigs and Floating Production Storage and Offloading Systems (FPSOs), risk serious damage from violent events in high seas. During slamming the hull of a ship collides rapidly with the water surface generating dangerously large hydrodynamic loads. These loads may also produce violent vibrations throughout the body of the ship, a phenomenon known as whipping. Both slamming and whipping are highly perilous for ship safety and can cause major structural damage and even lead to vessel breakup. On the 18th January 2007 the 62,000 tonne container ship MSC Napoli (shown in Figure 1) was lost in heavy seas in the English Channel. Catastrophic damage to the ship hull caused by wave slamming led to a GBP120,000,000 clean-up operation lasting two and a half years.

The official disaster report **[corroborating source A]** was released documenting the catastrophic effect of wave slamming. In the media it was stated that:

> *"The analytical study concluded that though the ship had been built with superior quality structured components, the lack of calculation of space and construction provisos led to its unprecedented accident"*
>
> **[corroborating source B, page 4]**

Economic loss is not the most serious issue when large ships capsize. In 1994 the ferry MS Estonia capsized in the Baltic Sea when a slamming event caused its bow ramp to fail, allowing water into the vehicle deck, the ship to sink and 852 lives to be lost.

An expert knowledge of the dynamics involved in such violent events is crucial for the design of ships and offshore structures. This includes knowledge of the forces generated during slamming and of the stresses created throughout the structure of the ship during whipping. It requires a deep understanding of the highly complex fluid-structure interaction between the ship and the water. The loads involved are so massive that even apparently rigid structures deform elastically. Design processes to mitigate the risk of damage require resource-intensive CFD modelling for the fluid motion, and finite-element codes for the structural response of the ship. But these approaches must be guided by a fundamental understanding of the dynamics of the problem obtained through mathematical modelling. To add to the challenge, a computational interface module must be carefully designed to allow the standalone CFD and finite-element codes to communicate.

Interface design remains a highly challenging task for which deep mathematical understanding of the whole problem is essential.

Professor Korobkin's research has led to a methodology for the rational and reliable assessment of the structural integrity and thus safety of ships and their cargos in severe sea conditions.

Bureau Veritas
The commercial application of Professor Korobkin's new theoretical results has been critical to cultivating a long-term relationship with Bureau Veritas. In 2005, Professor Korobkin carried out small, joint research projects financially supported by Bureau Veritas, which then led to, successful grant bids, joint scientific publications (e.g. R5) and a book chapter in UK Success Stories in Industrial Mathematics, which showcases successful collaborations between academia and industry. **[corroborating source C]**

Bureau Veritas is a world leader in the marine and offshore industry specialising in quality, health and safety and environment management, providing laboratory testing, inspection and certification services. Its network is spread across 140 countries, and it has around 74,000 employees serving more than 450,000 customers worldwide. Of those employees, 2,650 are marine and offshore experts, who establish and maintain technical standards for the construction and operation of ships and offshore structures. They can certify that the construction of a vessel complies with relevant standards and ensure continuing compliance with those standards. Certification is required to be able to register a vessel and obtain insurance. Classification societies such as Bureau Veritas verify that the vessel is in compliance with the classification standards of the society whose operations are accredited by the world's largest national and international organisations

Our impact on the company
Professor Korobkin works with the research department in Bureau Veritas' Marine Division to fundamentally improve their existing tools and methodologies for modelling hydro-structure interactions including slamming. The extreme complexity of the modelling challenge has made this a long-term and ongoing relationship from which both parties have benefitted.

Bureau Veritas recognises that:

> "*Professor Korobkin is the world leader on the topics of impact, especially related to semi-analytical approaches, which usually give the clearest insight into the Physics of the problem*".
>
> **[corroborating source D]**

In the current reporting period, several critical technical guidelines and notes at Bureau Veritas were modified or improved as a direct result of Professor Korobkin's work:

> *"The technical departments of the Bureau Veritas must be able to properly assess the risks related to the different impact problems which occurs during the operations of the ships and the off-shore floating units. In that respect, the research cooperation between Bureau Veritas and UEA is extremely useful for the improvement of the existing tools and methodologies for hydro-structure interactions. At the same time several critical technical Guidelines Notes were modified/improved thanks to the results of this cooperation".*
>
> **[corroborating source C, page 7]**

For example, the Software Solutions for Marine and Offshore Brochure **[corroborating source E]** presents new software developed at Bureau Veritas that is directly based on Professor Korobkin's research work in R1. Professor Korobkin's work on hydro-structure interactions in R5 was adopted by Bureau Veritas for their everyday work:

> "*The results of the cooperation showed to be extremely useful for our company, and the tools and methodologies, which were developed, are used on a daily basis in practice."*
>
> **[corroborating source D]**

The models created by Professor Korobkin represent the current state-of-the-art. Bureau Veritas note that:

> "The *cooperation with Prof. Korobkin has brought us significant added value and*

serious advantages in front of our competitors…..Without input from Professor Korobkin, our business model would be significantly affected and much less attractive to our clients."

[corroborating source D]

The cooperation enabled Bureau Veritas to pull ahead of their competition:

"we were the first Classification Society, which built the hydro-structure model for whipping with the consistent Generalized Wagner Model for slamming included, and this slamming model was developed with the great help of Prof. Korobkin during the years 2014-2015".

[corroborating source D]

The Bureau Veritas software suite HOMER

Professor Korobkin's vital role in the development of Bureau Veritas' software suite, HOMER **[corroborating source E, page 6]**, is of particular importance. This software is used for direct hydro-structure interaction calculations, specifically computing the structural response of a floating unit facing given wave conditions:

"The work of Professor Korobkin is directly implemented into our hydro-structure interaction software HOMER (2005-2020) for the purpose of consistent modelling of the whipping phenomena….and represent the state of the art on the subject."

[corroborating source D]

HOMER is used by more than 15 research and engineering institutions worldwide including major shipyards such as Daewoo, Hyundai Heavy Industry, Samsung Heavy Industry and Chantier de l'Atlantique, (with a combined turnover of about USD29,100,000,000 per year and employing 27,200 people), and engineering companies including Single Buoy Mooring (4,700 employees; turnover USD2,200,000,000 per year). Universities including those in Trondheim, Seoul, Busan, Zagreb and Kyushu also use the software. These companies and institutions use HOMER to perform calculations to determine the structural response of a floating unit facing given wave conditions, and to assess the fatigue life of the structure.

5. Sources to corroborate the impact

[A] *Report on the investigation of the structural failure of MSC Napoli English Channel on 18 January 2007*, Marine Accident Investigation Branch, Report No 9/2008, April 2008.

[B] The MSC Napoli Accident: Causes and Aftermaths – Article from Marine Insight 08.11.2019

[C] Book chapter: **Korobkin, A.**, & Malenica, S. (2016) Rational assessment of fluid impact loads. In *UK Success Stories in Industrial Mathematics* (pp. 99-105), Springer.

[D] Testimonial Letter from the Research Department Deputy Director at Bureau Veritas, 24.02.2020

[E] Software Solutions Brochure from Bureau Veritas with further details about the HOMER software on **page 6**. Downloaded on 16.11.2020 from marine-offshore.bureauveritas.com/software