Research Article
Open Access
CrossMark

Development in calculation and analysis of collision and grounding on marine structures and ocean engineering fields

Abstract

Various activities are conducted in oceanic territory in order to fulfil numerous demands. Ship has important role in these activities as transportation, supplier, and vessel which also directly connects with marine structures, such as offshore platform. Complex function of each facilities in this field makes chain reaction of one event can be remarkable and fatal. Accidental load becomes major consideration in operation of these marine and ocean facilities with famous example of accident phenomenon Titanic and Exxon Valdez have made related parties to perform sustainable analysis to develop assessment method, refine formula, propose prevention system, mitigation scheme, structural behavior, etc. In present work, a brief discussion in collision and grounding for related objects in scopes of marine structure and ocean engineering. The introduction is presented in initial part as presenting background, importance, and implication of impact engineering. Several examples are addressed to observe contribution this part in history of naval architecture. In next section, discussion is given in specific fields, namely ocean and marine engineering. Implementation of impact and accidental load are presented in conceptual method and material preparation. Results are described as milestone of collision and groundings' development. In later section, conclusion is summarized based on discussion and recommendation in performing analysis and calculation for collision and grounding are covered.

Keywords: Marine structures, Ocean engineering, Impact engineering, Collision, Grounding, Assessment method, Finite element method, Environmental pollution, Structural damage, Probabilistic of scenario and casualty

Volume 5 Issue 2 - 2017

Aditya Rio Prabowo,[1] Dong Myung Bae,[2] Jung Min Sohn,[2] Ahmad Fauzan Zakki,[3] Bo Cao[4]

[1]Marine Convergence Design, Pukyong National University, South Korea
[2]Naval Architecture and Marine Systems Engineering, Pukyong National University, South Korea
[3]Naval Architecture, Diponegoro University, Indonesia
[4]China Shipbuilding Industry Corporation Economic Research Center, China

Correspondence: Aditya Rio Prabowo, Pukyong National University, Nam-gu, Yongso-ro 45, Daeyeon-dong, Busan 48513, South Korea, Tel 82 (0) 51 629 6613, Fax 82 (0) 51 629 6608, Email aditya@pukyong.ac.kr

Received: October 20, 2016 | **Published:** February 15, 2017

Abbreviations: BWH, Bressan Williams and Hill; FLD, Forming Limit Diagram; GL, Germanischer Lloyd; IOPCF, International Oil Pollution Compensation Funds; LR, Lloyd's Register; RTCL, Rice-Tracey and Cockcroft-Latham

Introduction

An impact load occurs accidentally which may lead to other chain reaction as prevention of it is not provided in same time as the load takes place. In engineering, impact implicitly indicates a negative situation which may deliver enormous casualties of involved objects, e.g. train crash,[1] emergency landing of airplane,[2] free-fall lifeboat,[3] etc. Each of these events has been analyzed to predict damage and design a mitigation and safety. However, as its nature as accidental form, scenario of impact phenomenon may be limitless as numerous parameters are involved. Equally with action, there is always reaction force which in opposite direction and same magnitude. This statement on Newton's third law of motion indicates that if the scenario as action is limitless, then the result will also endless. This characteristic of impact makes this field is continuously studied by researchers from various disciplines. Start with basic material, Ozguc et al.[4] proposed implementation of plastic-kinematics material in modelling deformable ship structure for side collision which was adopted and improved by Bae et al.[5] using real-life accident specimen and laboratory testing and experiment. In more detailed level, Ludwik's strain hardening was defined and presented by Hutchinson & Neale.[6] Material and structure have close correlation as both of them become major parameters in occurrence of damage extent. An instance for approach of damage modelling is Forming Limit Diagram (FLD) as mentioned by Keeler & Backofen[7] and Jie et al.,[8] the Rice-Tracey and Cockcroft-Latham (RTCL) model as implemented by Alsos & Amdahl,[9] Alsos et al.[10] and The Bressan, Williams, and Hill (BWH) model in Alsos et al.[11]

The mechanism of rupture and failure of construction system is considered in macro level destruction before, during and after impact. Accurate condition of the three conditions will provide good estimation in behavior of involved structure in impact. One of known method to assess the mechanism is simplified analytical method. Zhang[12] stated that the concept of this method is based on the upper-bound theorem and some assumption from observations of accidental damages and experimental studies. Usually, the method can give good predictions through a fast simple analysis. Furthermore in collision, a major assumption in the simplified analytical method is that different structural members, such as side shell. Decks, and frame do not interact but contribute independently to the total collision resistance. In marine accident field, several researchers have proposed their work as in assessment method in minor collision by McDermott et al.,[13] simple method was introduced by Reckling[14] in calculation of absorbed energy by the involved ships, Kinkead[15] developed an analytical technique for the calculation of critical velocities, which the results was compared with a modified Minorsky[16] formula. Other researches in the structural mechanism were carried after 1983 until 1997 by Hysing[17] and Scharrer[18] for assessment of Ro-Ro passenger, Wang & Ohtsubo[19] in failure modes of plates, and Amdahl,[20] Yang & Caldwell[21] and Kierkegaard[22] for researches on bow crushing.

These efforts are addressed to continuously improve safety and prevention subjected impact load. In ocean engineering, marine pollution becomes remarkable damage as environment is destructed by oil spill. High-profile accident of Exxon Valdez is good example of this description as millions gallons of oil spilled and severely damaged water ecosystem of Alaska. Several species are classified extinct and others are considered unknown. In matter of marine pollution by oil spill, statistic of International Oil Pollution Compensation Funds IOPCF[23,24] indicated that this phenomenon occurred as chain reaction of two impact form in ocean, namely collision and grounding with their contributions 52% from overall cases which also presented by Lloyd's Register ten years beforehand. Illustration by Zhang,[12] Törnqvist[25] and Yamada[26] presented how massive damage on water territory which in reality, not only by oil spill by shuttle tanker Hu[27] but also by ship wreck as ship sinking after experiencing impact. Besides environmental damage, human casualties are occurring as collision and grounding take place. The tragic losses of several Ro-Ro passenger ships, such as European Gateway in 1982, Herald of Free Enterprise in 1987, and catastrophe of Estonia in 1994 with loss of more than 800 lives, led to reassessment and improvement for safety of passenger vessels in many countries.

This work is addressed to provide brief review in collision and grounding which in same time provides useful reference in preparation, procedure, results for these phenomenon. Recommendation is summarized together conclusion in final part as overall review of present discussion will be presented.

Discussion

As introduced before, in marine and ocean engineering, collision and grounding are remarkable phenomenon which provide large casualties after take place. The discussion in this section will be directed to observe assessment process of collision and grounding. Considerable parameters in order to refine result is presented. The main calculation method in present discussion is finite element method. As rapid development of computational code and instrument, as well as good implementation in analyses of aircraft and military vehicle, this method is introduced in naval architecture and marine engineering fields. This method is judged powerful enough to produce reliable result even for nonlinear and dynamic phenomenon, such as explosion, collision, and grounding.[28] Cost for material experiment and testing can be reduced as low as possible since modelling can cover until detail aspect of phenomenon. Failure in analysis can be fixed and modified model may be able to be simulated as soon as it is ready. However, in modelling and simulating phenomenon which involves high nonlinearities, procedure in defining configuration and setting will useful to reduce time process. Bathe[29] proposed basic concept that have to be understood by user before they enhance with modelling process. The finite element method is used to solve physical problems in engineering analysis and design. In process, user can of course only obtain insight into the physical problem which can be considered that user cannot predict the response of the physical problem exactly because it is impossible to reproduce even in the most refined mathematical model all the information that is present in nature and therefore contained in the physical problem. In this case, the user has to be able to define how detail he/she should perform modelling for phenomenon object. More detail of model is considered well in accuracy but not in case of time process, and same with rough model it will be good in time process but may be worse in case of reliability. Accounting for accuracy, the finite element analysis solves this mathematical model. Since the finite element solution technique is a numerical procedure, it is necessary to assess the solution accuracy. If the accuracy criteria are not met, the numerical (i.e. finite element) solution has to be repeated with refined solution parameters (such as finer meshes) until sufficient accuracy is reached. Other way to verify configuration in finite element model is by conducting benchmark study. Benchmark can be taken from previous research using laboratory experiment, field survey, and even other numerical study. Re-modelling and simulating benchmark will ensure error level of present method which lower error level will be preferred. In impact, several researchers offer reliable reference to be considered as benchmark, such as Yu et al.,[30] AbuBakar & Dow[31] and Liu & Soares[32] in grounding phenomenon.

While in collision, previous works of Lehmann & Peschmann,[33] Wiśniewski & Kołakowski,[34] Hong & Amdahl,[35] and Prabowo et al.[36] can be used as reliable reference. These works were conducted by various methods, including finite element method, analytical concept, field survey of real-life phenomenon, and laboratory testing. Interest of researcher can lead to preference of calculation method. The indication these works that each method needs verification, except laboratory test. This method often is used directly as benchmark and will be expanded based on objective of researcher. The accuracy may be high and can be solid reference for further works. However, other input such as time and funding are very costly, which in some cases, experiment are found fail. Consideration in method should be conducted carefully as the final conclusion is determined how user calculates input parameter and model.

In case of numerical calculation, configuration of physical material is highly influenced by failure criterion. Several criterion are presented by Germanischer Lloyd,[37] RTCL criterion,[38,39] BWH method[10] and Lehmann & Peschmann's formulae.[33] As mentioned in Section 1, known researchers have proposed their concepts in damage modelling. This concept is correlated with meshing size in numerical model. Therefore, essential parameter in modelling beside user defined parameters is meshing size. High deformation area should be applied the finest mesh in order to capture stress and strain contours as well as damage pattern on it. Other application of failure criterion is to limit meshing size that will be implemented on model. Bigger size will give faster results but rough contour which may led to wrong assumption in discussion. Nevertheless, meshing with too small size will be time consuming. In this case, optimum size of meshing can be obtained. Reference for deepening knowledge in this field, previous work of Ehlers et al.[11] is recommended to be used. Discussing failure will direct the focus on other component that highly influence calculation result, namely mechanical properties for involved objects in impacts. Material model can be referred based on previous work of researchers in collision and grounding. This option is taken as it is cheap and simple to be implemented. This concept has been improved with implementation of material experiment and testing data such as by Bae et al.[5] Even though more time is needed with larger research funding, satisfactory is achieved and can be reliable reference for various analyses which not only collision, but also grounding, stranding, explosion, etc. In aspect of material, during impact with foreign object as found in grounding and stranding, proper modelling of material properties is an important stage as defining sea bottom contour which is modelled by Zilakos et al.[40] and assessed by Sormunen et al.[41] In his recent work, Prabowo et al.[42] proposed material model for rock to be implemented in hard grounding and stranding. This material is assumed as a rock which is dominated by pyroxene mineral which Poisson's ratio and wave velocity characteristic of this material are presented by Christensen.[43]

After physical properties for model is defined, important matters that need to be assured are setting and configuration of numerical model. The basic concept of finite element is defining real-life phenomenon into virtual arrangement which will be divided by according to determined meshing size. Therefore it is necessary to consider virtual element and related parameters. Firstly, element formulation is presented in this scope of discussion. As wide application of numerical codes for simulation, definition of element is an absolute stage that should be defined in order to run a simulation. In collision and grounding, the ships are generally defined as shell element which is stated by ANSYS[44] that there are several options that can be used to involved models, such as Belytschko-Tsay, Belytschko-Wong-Chiang, Hughes-Liu, etc. Other form of element is also proposed by Hallquist,[45] for instance Belytscho-Lin-Tsay and Marchertas-Belytschko. Concern to provide reliable result in reasonable time process are found quite significantly affected by this parameter. Implementation in ship grounding by Zhang and Suzuki[46] and collision investigation by Bae et al.[5] conclude that Belytschko-Tsay formulation produces similar result with other proposed elements with difference in time process more than 50% than the element which produces largest time process. Despite its advantage, user should remember that in collision and grounding are classified as phenomenon that involve high nonlinearity and dynamic throughout the process. Hourglassing phenomenon is predicted will occur in these calculations which can reduce reliability of results. In order to observe behavior of this phenomenon, Prabowo et al.[42] implemented different element formulation that generally used by researchers in grounding, for example.[9] By implementing fully integrated Belytschko-Tsay element, the hour glassing is found zero during impact between double bottom structure and sea bottom. Even though it is good to get reliable result, the time process for this element is also observed higher than ordinary Belytschko-Tsay element, which should be included in consideration.

In calculation result, distribution data of ship structure and size into damage extent had been successfully calculated by Pedersen & Zhang.[47] In other reference, combination calculations are performed to observe longitudinal strength of ship after collision. Researchers such as Ozguc et al.[4] performed this combination on bulk carrier tanker. Simonsen[48,49] provided detail explanation regarding tearing mechanism in hard grounding case which is also defined in Simonsen.[50] In impact study, merchant ship tends to be an observation object as it has high probability to experience such load. Demand to expand the studies to other marine vessels is fulfilled by Otto et al.[51] and Prabowo et al.[52] as Ro-Ro passenger ship is taken as observation object, where Otto directed his study on risk analysis for collision and grounding, and Prabowo focused his attention to structural behavior accounting for external dynamics of ship collision. Investigation of structural performance under impact load, especially in shoal grounding case was carried by Yu et al.[53] where in ship collision case, concern on double hull design against impact load, failure, and oil spill were addressed by Hong and Amdahl,[35] Pedersen & Li,[54] Yip et al.[55] and Hegazy et al.[56] Correlating with structural concern, as opening of northern sea route through arctic sea, study of impact is expanded into polar and arctic conditions which involve ice as indenter in impact process. Formulation for this case was developed by Liu & Amdahl[57] which was implemented in numerical analysis by Liu et al.[58] Specific scenario in collision of double hull tanker by level ice was conducted by Cao et al.[59] that concluded in side penetration by level ice, inner hull still in safe condition. Indication of improvement in material properties under polar condition is widely open as previously was initiated by Daley[60] for empirical formula in calculating ice characteristic, Jones et al.[61] and Kim[62] in ice modelling, Min et al.[63] for mechanical properties for steel in extreme condition, and structure-ice interaction by Gagnon & Derradji-Aouat[64] which was later implemented in compressive ice scenario by Bae et al.[65] These references indicate that proper modelling should be performed not only on the ship but also striking object, as ice in collision and sea bottom in grounding. Different treatment should be performed, for instance referring into solid reference for mechanical properties and material characteristic. Concern should also be paid on environmental condition which later highly affects material and result.

Conclusion

This paper was described a brief discussion based on review of various references in impact engineering of marine structure and ocean engineering. The focus had been paid on ships collision and grounding which was found in this discussion delivered remarkable amount of casualties on various parties. Demand to improve safety and develop prediction for these phenomenon made analysis and investigation were conducted widely, which needed proper consideration in modelling and simulation.

There were indeed numerous parameters that could affect calculation result, which were sorted into main parameters as described in this work. As its nature, finite element method was used for obtaining fast estimation for various science and engineering phenomenon. Therefore, definition of real-life condition should be carefully performed, especially for meshing size. References indicated that meshing characteristic hold important effect to simulation results, including stress contour and deformation pattern. Next consideration was directed to material characteristic for both of physical and virtual conditions. Firstly. In physical part, modelling of rupture and failure was recommended to be determined in order to obtain meshing size for involved objects. Secondly, element formulation was observed essential in collision and grounding simulations as it was main part of numerical model, which was included in virtual part. These consideration were presented to achieve goal setting of finite element method (FEM) itself which the calculation results should be obtained in highest possible reliability level and reasonable time process, since it was impossible to get exact result as real-life phenomenon by FEM even in most refined mathematical model.

Results of researches for collision and grounding mainly using merchant ships as observation objects since they were frequently sailing to meet its objective function and designated target, made chance to experience impact load, and also as demand rising to ensure safety for cargo, crew, passenger, and ship itself, this kind of ship was generally used in calculation. Structural conditions prior and after rupture were main interest as mechanism of failure and structural performance dominated calculation results. Probabilistic and statistic were used to present finding and tendency for these simulations. Expanded study in grounding with sea bottom and collision with ice proposed that sufficient amount of attention should be addressed in material modelling for indenter. This was considered vital since contribution of foreign object in impact was highly influencing observed structural behaviors. Chance is widely distributed for concern in modelling of sea bottom and ice form, which furthermore, collision with part of other marine facilities, such as container, rigid wall (jetty), solid rod, and log are seriously encouraged by present authors to be conducted. Concern of casualties should be directed not only on ship structure, but also on indenter, such in case of collision with container that carries dangerous items (e.g. nuclear waste), and oil/fluid which has potential to inflict any environmental damage, since this kind of commodities can be transported using flexi-tank, which provides new research potential in impact load problem for marine structures and ocean engineering fields.

Acknowledgements

This work was successfully carried out in Laboratory of Ship Structure and Vibration Analysis, Department of Naval Architecture and Marine Systems Engineering, Pukyong National University, South Korea. The authors would like to offer their gratitude to Mr. Irfan Taufiqurrahman, Mr. Teguh Fajar Basuki and Mr. Reza Andriyan Saputro who all of them from PT Samudra Marine Indonesia (SMI) Cilegon Branch, West Java, Republic of Indonesia for guiding location and ship surveys on repair process of an involved ship in collision, and also to nameless reviewers who paid their time and attention in checking present work.

Conflicts of interest

None.

References

1. Klinger C, Bohraus S. 1992 Northeim train crash –A root cause analysis. *Engineering Failure Analysis*. 2014;43:171–185.
2. James MN. Crashing aircraft, sinking ships – fractographic and SEM support for unusual failure hypotheses. *Engineering Failure Analysis*. 2002;9(3):313–328.
3. Zakki AF, Windyandari A, Bae DM. The development of new type free–fall lifeboat using fluid structure interaction analysis. *Journal of Marine Science and Technology*. 2016;24(3):575–580.
4. Ozguc O, Das PK, Barltrop N. A comparative study on the structural integrity of single and double side skin bulk carriers under collision damage. *Marine Structures*. 2005;18(7–8):511–547.
5. Bae DM, Prabowo AR, Cao B, et al. Study on collision between two ships using selected parameters in collision simulation. Journal of Marine Science and Application. 2016;15(1):63–72.
6. Hutchinson JW, Neale KW. Sheet necking – III. Strain–rate effects. *Mechanics of sheet Metal Forming*. 1978;pp.269–285.
7. Keeler SP, Backofen WA. Plastic instability and fracture in sheets stretched over rigid punches. *Transactions ASM*. 1963;56(1):25–48.
8. Jie M, Cheng CH, Chanb LC, et al. Forming limit diagrams of strain–rate–dependent sheet metals. *International Journal of Mechanical Sciences*. 2009;51(4):269–275.
9. Alsos HS, Amdahl J. On the resistance of tanker bottom structures during stranding. *Marine Structures*. 2007;20:218–237.
10. Alsos HS, Amdahl J, Hopperstad Odd S. On the resistance to penetration of stiffened plates. Part II –Experiments. *International Journal of Impact Engineering*. 2009;36(7):875–887.
11. Ehlers S, Broekhuijsen J, Alsos HS, et al. Simulationg the collision response of ship side structures: A failure criteria benchmark study. *International Shipbuilding Progress*. 2008;55:127–144.
12. Zhang S. The mechanics of ship collisions. PhD thesis, Technical University of Denmark. 1999.
13. McDermott J, Kline R, Jones E, et al. Tanker structural analysis for minor collisions. SNAME Transactions. 1974.
14. Reckling KA. Mechanics of minor ship collisions. *International Journal of Impact Engineering*. 1983;3(1):281–299.
15. Kinkead AN. A method for analyzing cargo protection afforded by ship structures in collision and its application to an LNG carrier. *RINA Transactions*. 1980;299–323.
16. Minorsky VU. An analysis of ship collision with reference to protection of nuclear power plants. *Journal of Ship Research*. 1959;3(2):1–4.
17. Hysing T. Damage and penetration analysis –safety of passenger/RoRo vessels. *DNV Report No*. 1995;95–0419.
18. Scharrer M, Ostergaard C. Safety of passenger/RoRo vessels–Analysis of collision energies and hole sizes. *GL Report No*. 1996;FL96.009.
19. Wang G, Ohtsubo H. Deformation of ship plate subjected to very large load. The 16th International Conference on Ocean, Offshore, and Arctic Engineering (OMAE), Japan. 1997.
20. Amdahl J. Energy absorption in ship–platform impact, *Norwegian Institute of Technology Report No. UR*. 1983;83–34.
21. Yang PDC, Caldwell JB. Collision energy absorption of ship bow structures. *International Journal of Impact Engineering*. 1988;7(2):181–196.
22. Kierkegaard H. Ship bow response in high energy collisions. *Marine Structures*. 1993;6(4):359–376.
23. IOPCF. Annual report 2005. International Oil Pollution Compensation Funds. 2005.
24. IOPCF. International regime for compensation for oil pollution damage. International Oil Pollution Compensation Funds.
25. Törnqvist R. Design of crashworthy ship structures. PhD thesis, Technical University of Denmark. 2003.
26. Yamada Y. Bulbous buffer bows: A measure to reduce oil spill in tanker collisions. PhD thesis, Technical University of Denmark. 2006.
27. Hu C. Risk analysis for shuttle tankers and mitigating measures. The 17th International Conference on *Ocean, Offshore, and Arctic Engineering (OMAE)*, Portugal. 1998.
28. Kitamura O. FEM approach to the simulation of collision and grounding damage. *Marine Structures*. 2002;15(4–5):403–428.
29. Bathe KJ. Finite element procedures. Prentice–Hall, Inc, New Jersey, USA. 1996.
30. Yu Z, Hu Z, Wang G. Plastic mechanism analysis of structural performances for stiffeners on bottom longitudinal web girders during a shoal grounding accident. *Marine Structures*. 2015;40:134–158.
31. AbuBakar A, Dow RS. Simulation of ship grounding damage using the finite element method. *International Journal of Solids and Structures*. 2013;50(5):623–636.
32. Liu B, Soares CG. Simplified analytical method for evaluating web girder crushing during ship collision and grounding. *Marine Structures*. 2015;42:71–94.
33. Lehmann E, Peschmann J. Energy absorption by the steel structure of ships in the event of collisions. *Marine Structures*. 2002;15(4–5):429–441.
34. Wiśniewski K, Kołakowski P. The effect of selected parameters on ship collision results by dynamic FE simulations. *Finite Elements in Analysis and Design*. 2003;39(10):985–1006.
35. Hong L, Amdahl J. Crushing resistance of web girders in ship collision and grounding. *Marine Structures*. 2008;21(4):374–401.
36. Prabowo AR, Bae DM, Sohn JM, et al. Evaluating the parameter influence in the event of a ship collision based on the finite element method approach. *International Journal of Technology*. 2016;7(4):592–602.
37. GL. Development of explanatory notes for harmonized SOLAS chapert II–1. International Maritime Organization. 2003.
38. Rice J, Tracey D. On the ductile enlargement of voids in triaxial stress fields. *Journal of Mechanics and Physics of Solids*. 1969;17(3):201–217.
39. Cockcroft MG, Latham DJ. Ductility and the workability of metals. *Jpn I st Met*. 1968.

40. Zilakos IK, Toulios M, Nguyen TH, et al. Simulation of the response of double bottoms under grounding actions using finite elements. The 2nd International Conference *on Marine Structures–Analysis and Design of Marine Structures, Portugal*. 2009;pp.305–311.

41. Sormunen OVE, Castrén A, Romanoff J, et al. Estimating sea bottom shapes for grounding damage calculations. *Marine Structures*. 2016;45:86–109.

42. Prabowo AR, Bae DM, Sohn JM, et al. Predicting the structural damage of double hull during stranding. The 1st International Joint Conference on Science and technology (IJCST), Indonesia. 2016b.

43. Christensen NI. Poisson's ratio and crustal seismology. *Journal of Geophysical Research*. 1996;101(B2):3139–3156.

44. ANSYS. ANSYS LS–DYNA user's guide. ANSYS, Inc., Pennsylvania, USA. 2013.

45. Hallquist JO. LS–DYNA3D theoretical manual. *Livermore Software Technology Corporation, California*, USA. 1993.

46. Zhang A, Suzuki K. Numerical simulation the bottom structures grounding test by LS–DYNA. The 5th European LS–DYNA Users Conference, United Kingdom. 2005.

47. Pedersen PT, Zhang S. Effect of ship structure and size on grounding and collision damage distributions. *Ocean Engineering*. 2000;27(11):1161–1179.

48. Simonsen BC. Ship grounding on rock –II. Theory. *Marine Structures*. 1997a ;10:563–584.

49. Simonsen BC. Ship grounding on rock –II. *Validation and application. Marine Structures*. 1997b ;10:563–584. Simonsen BC, (1997c) Mechanics of ship grounding. PhD thesis, Technical University of Denmark.

50. Simonsen BC. Mechanics of ship grounding. PhD thesis, Technical University of Denmark. 1997c.

51. Otto S, Pedersen PT, Samuelides M, et al. Element of risk analysis for collision and grounding of a RoRo passenger ferry. *Marine Structures*. 2002;15(4–5):461–474.

52. Prabowo AR, Bae DM, Cao B, et al. The study of selected parameters on ship collision based on finite element method approach. The 6th International Symposium on Advanced Engineering (ISAE), South Korea. 2015.

53. Yu Z, Hu Z, Amdahl J, et al. Investigation on structural performance predictions of double–bottom tankers during shoal grounding accidents. *Marine Structures*. 2013;33:188–213.

54. Pedersen PT, Li Y. On the global ship hull bending energy in ship collisions. *Marine Structures*. 2009;22(1):2–11.

55. Yip TL, Tallet WK, Jin D. The effectiveness of double hulls in reducing vessel–accident oil spillage. *Marine Pollution Bulletin*. 2011;62(11):2427–2432.

56. Hegazy ASH, Badran SF, Youssef SA. Structural design of double hull oil tankers for collision. *Port Said Engineering Research Journal*. 2013;16(2):61–67.

57. Liu Z, Amdahl J. A new formulation of the impact mechanics of ship collisions and its application to a ship–iceberg collision, *Marine Structures*. 2010;23(3):360–384.

58. Liu Z, Amdahl J, Løset S. Integrated numerical analysis of an iceberg collision with a foreship structure. *Marine Structures*. 2011;24(4):377–395.

59. Cao B, Bae DM, Sohn JM, et al. Numerical analysis for damage characteristics caused by ice collision on the side structure. The 35th International Conference on Ocean, Offshore, and Arctic Engineering (OMAE), South Korea. 2016.

60. Daley C. Energy based ice collision forces. *The 15th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC)*, Finland. 1999.

61. Jones SJ, Gagnon RE, Derradji A, et al. Compressive strength of iceberg ice. *Canadian journal of Physics*. 2003;81(1–2):191–200.

62. 11Kim H. Simulation of compressive 'cone–shaped' ice specimen experiments using LS–DYNA. 13th International LS–DYNA Users Conference. 2014.

63. Min DK, Shim CS, Shin DW, et al. On the mechanical properties at low temperatures for steels of ice–class vessels. *Journal of the Society of Naval Architects of Korea*. 2011;48(2):171–177.

64. Gagnon RE, Derradji–Aouat A. First results of numerical simulations of bergy bit collisions with the CCGS Terry Fox icebreaker. The 18th IAHR International Symposium on Ice, Japan. 2006.

65. Bae DM, Cao B, Prabowo AR. A study on the damage characteristics of collision on the side structure. International Conference of Ship and Offshore Technology (ICSOT), Indonesia. 2015.