Seaway Loads Applied to a Frigate by the Smoothed Particle Hydrodynamics Technique

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ABSTRACT

Reduction of maintenance and life-cycle management costs of ships and offshore structures remains a major concern for both naval and commercial operators. Accordingly, the development and utilisation of improved loads and degradation modelling and structural assessment tools are required. This includes the incorporation of non-linearities due to the fluid-structure interaction (FSI), because non-linear loads can considerably contribute to the long-term stresses and structural damage. Smoothed Particle Hydrodynamics (SPH), a mesh-free particle method, can provide a cost-effective and robust solution to determining the non-linear responses of ships in long crested waves.

This paper presents a summary of developments within the Structural Integrity of Maritime Platforms (SIoMP) project. The paper describes the implementation of SPH, coupling between SPH and Finite Element (FE) analysis, and the extraction of loads and stresses from a model of a naval ship. A key aspect of the analysis is the exploitation of a technique to develop regular waves at constant amplitude over many wavelengths. Test cases are used to study the model sensitivity to various numerical parameters, and the results computed using the SPH-FE method are compared to those computed using a strip theory method. Based on the results of the sensitivity analysis appropriate domain boundaries (depth and width), and SPH particle diameter are recommended.

GLOSSARY

2D	Two-dimensional
3D	Three-dimensional
CFD	Computational fluid dynamics
FE	Finite element
FSI	Fluid structure interaction
H	Wave height (m)
L_{WL}	Waterline length (m)
p	Pitch response (rad)
p’	Non-dimensionalised pitch
SIoMP	Structural Integrity of Maritime Platforms
SPH	Smoothed particle hydrodynamics
v	Ship speed (kn)
VPS	Virtual Performance Solution
y	Heave response (m)
y’	Non-dimensionalised heave

INTRODUCTION

Robust and efficient numerical methods are increasingly being developed and exploited to analyse the hydro-elastic responses of ships to ocean waves [1]. The incorporation of non-linearities due to the fluid-structure interaction (FSI), and extreme seas, is important because non-linear loads can have a considerable influence on the long-term stresses and structural damage when compared to accounting for the linear wave response alone [2, 3].

There is a need to reduce maintenance and life-cycle management costs and to have the ability to conduct accurate service life extension review naval, and other, ships [9]. These needs may be met through the development and use of improved loads and structural assessment tools.

Different methodologies to predict the external loads and structural responses of a ship in a seaway are available (Figure 1) [4]. These have varying complexity and computational expense. Time-domain analysis like FSI, is considered more accurate but considerably more computationally expensive than frequency-domain and quasi-static procedures. In general, computational constraints have made time-domain analysis of ships for long-term structural assessment not feasible [5, 6]. However, recent hardware advances may result in time-domain analysis being more commonly used in the maritime industry [5, 7].

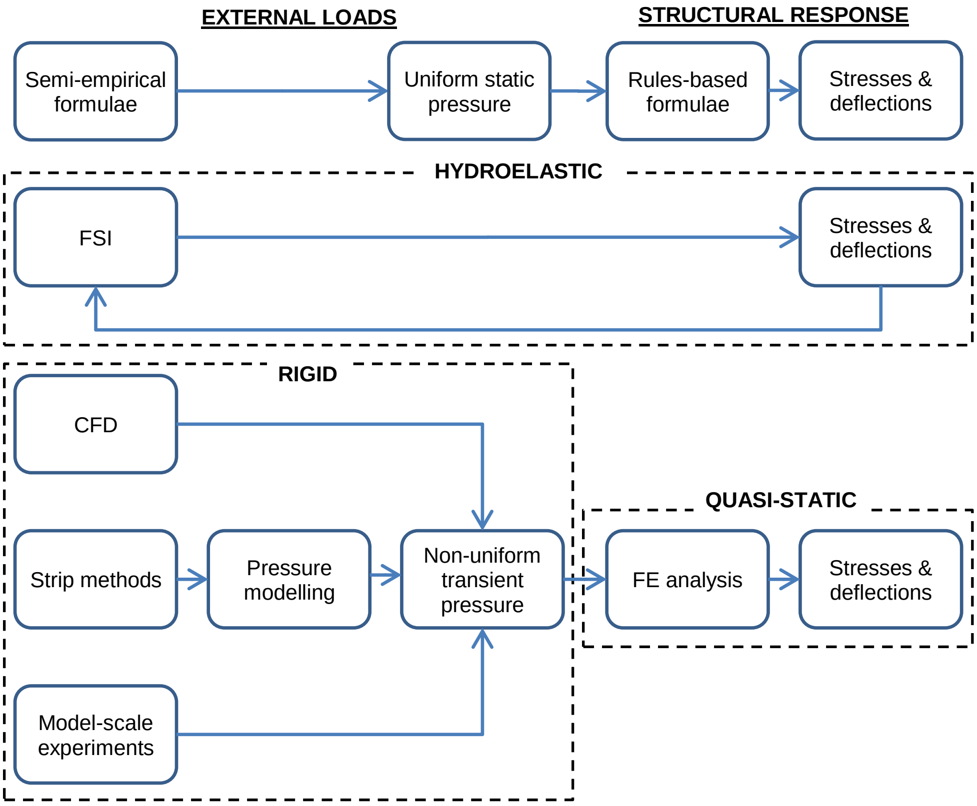

Figure 1: Schematic of different approaches for load and response assessment [4]

One type of hydro-elastic analysis is Smoothed Particle Hydrodynamics (SPH), a mesh-free particle method based on Lagrangian formulation. SPH can provide a cost-effective and robust solution to determining the non-linear responses of ships in long crested waves and of novel hullforms [7, 8].

This paper presents a summary of developments within the Structural Integrity of Maritime Platforms (SIoMP) project [10]. The aim of the SIoMP project is to improve the understanding of the effect of structural age-related degradation, due to long-term loads and corrosion, of naval and other ship and offshore structures. The paper describes the implementation of SPH, coupling between SPH and Finite Element (FE) analysis, the model set-up, and the extraction of loads and stresses. This is followed by test cases to study the model sensitivity to various numerical parameters, and presentation of a comparison between the results generated by the fully coupled SPH-FE methodology and a strip theory method. A key aspect of the analysis is the exploitation of a technique to develop regular waves at constant amplitude over many wavelengths [8].

METHODOLOGY

Smoothed Particle Hydrodynamics (SPH) and Implementation

Smoothed Particle Hydrodynamics (SPH) is a mesh-free particle based method that is particularly well-suited to modelling fluids and gases [11]. It was originally developed for modelling the development of galaxies and stars in astrophysics [12, 13]. Liu [11] provides a comprehensive review of the history and development of the commonly applied SPH formulations.

The mesh-free nature of SPH allows the investigation of complex fluid flows such as breaking waves, the parting of waves by the bow of the ship, green water on deck, and ingress of water into the ship through openings. These features are particularly difficult to handle efficiently in the grid-based schemes of conventional computational fluid dynamics (CFD).

The present paper uses the SPH implementation within the commercial software suite Virtual Performance Solution (VPS) [14]. VPS is a general purpose, multi-physics analysis tool, having a comprehensive material library that includes linear and non-linear material models.

Fluid Structure Interaction (FSI)

FSI is the analysis of the interaction and response of a fluid and a structure. In VPS, the SPH solver handles the fluid behaviour and the FE analysis solver handles the structure. These two solvers are integrated and are resolved simultaneously. The solution involves an explicit time-marching scheme. The time-step is chosen automatically by the software and is typically in the order of a fraction of a millisecond or so for metal structures.

To prevent structural elements from penetrating one another, VPS uses penalty-force sliding contact algorithms [15] along with an enhanced contact algorithm for the handling of discrete SPH particles interfacing with structural shell elements [16]. The contact interface between SPH particles and shell elements defines the distance that a SPH particle is allowed to approach a shell element (relative to the centre of the particle). It also defines any damping that may be applied to the contact, and the sliding friction that may exist. The project's experience to date has shown that a friction value of zero works well. The SPH and FE analysis solvers interact at each time-step through the contact interface. There is implied continuous and complete interaction of the fluid and the structure at every time step.

Modelling of Waves

The approach to model waves is to define a simulation domain, which is a portion of a large body of water. Deep-water waves are developed to be analogous to wind-generated waves that occur on the free surface of oceans. The edges of the simulation domain are established to respond in a way that mimics the larger ocean beyond the edges of the domain. One of the challenges of this simulation is determining the appropriate domain dimensions such that the finite domain is representative of the ocean environment.

This paper considers the case of a ship travelling into long-crested head seas. The simulation domain is a finite number of wavelengths in length, with upstream and downstream ends, depth, and width (Figure 2) [17].

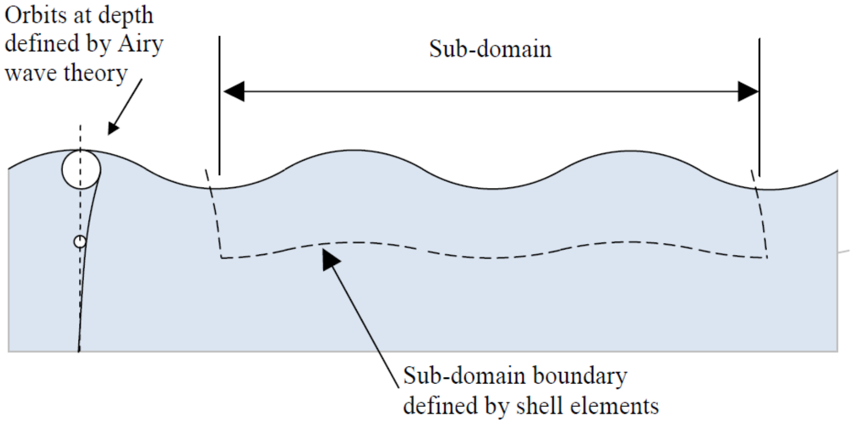

Figure 2: Concept of a subdomain for boundary definitions of moving floor [17]

All vertical edges of the simulation domain are defined by periodic boundary conditions. A periodic boundary condition is a numerical definition that can model an infinite length of fluid by passing fluid behaviour from one edge of the domain to the other continuously. For example, for a wave propagating through the domain, as the wave approaches the downstream end, the particles encounter the periodic boundary condition. This transfers their interactions to the upstream end of the domain. The wave will effectively be reinstated at the upstream end without any loss. Hence, the wave can propagate continuously through the domain.

The depth of the simulation domain is less than half the wavelength of interest. Thus, according to deep wave theory, the surface wave should create oscillatory motions of the water at that depth. The deep-water wave is simulated by assigning circular movements, equivalent to the orbital motion of the water, at the bottom of the domain. As a result, deep-water waves are simulated in a finite depth domain. When the motion of the bottom of the domain is in phase, and of the same frequency as the surface wave, the surface wave will propagate to mimic the deep water condition [18].

Modelling of Ship

The ship model used in the SIoMP project is a full-scale structural FE model of a frigate constructed of high-tensile steel. The global model comprises shell, beam and bar elements.

To enable the ship to establish an equilibrium in the water, the ship model commences the simulation at zero forward speed out of the water. Gravity is applied gradually to all elements and nodal masses of the ship, causing the ship to sink into the water to achieve equilibrium. Damping is applied to the SPH particles to prevent excessive movement during this period. For simulation at non-zero speed, the ship is accelerated to the desired speed.

For the case of head seas, the ship is restrained from sway and yaw by fixing a few nodes on the centreline at the bow and stern of the ship in lateral displacement. The ship is free to move in pitch, heave, and roll. Forward speed is fixed by a velocity boundary condition that acts on a group of nodes of the ship, close to where the propeller thrust would be developed on the ship.

Figure 3 presents a still shot of the FE model within the SPH domain during a simulation in regular waves.

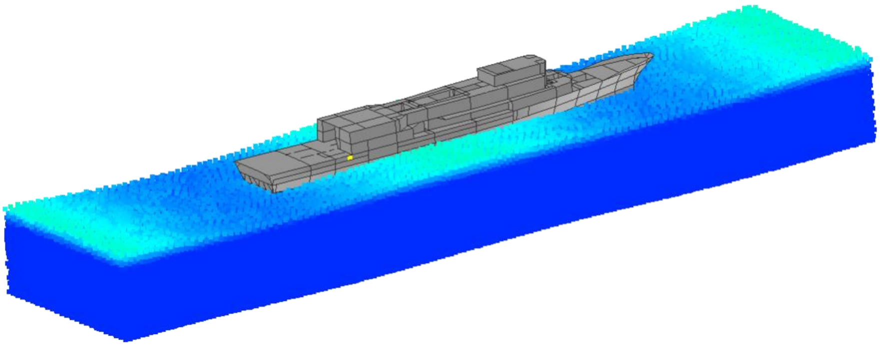

Figure 3: Example still shot of FE model of ship within SPH domain during a simulation

To extract the hydrodynamic loads, the hull is divided into athwartships strips between each frame with a unique contact interface defined for each of these strips with the water. The sum of these contact interfaces governs the response of the ship to the water. In addition, the contact force on each strip is stored, allowing post-processing to reveal the variation of forces along the hull with time. In still water at zero forward speed when the ship has come to equilibrium, the longitudinal distribution of the contact forces acting between each frame of the ship coincides with the distribution of buoyancy along the length of the ship. As waves develop and the ship moves relative to them, the forces developed on the hull induce the ship motions and responses.

The effect of added mass acting on the ship is not calculated as an 'added' component. Instead the effect of added mass is developed in the same way the real ship experiences the effect of added mass. That is, the SPH particles in close proximity to the ship are influenced by the presence of the ship, and are thus accelerated or decelerated to allow the ship to occupy that volume of water.

TEST CASES

To demonstrate the application of the SPH-FE methodology, test cases are presented. This includes a study of the effect of the model sensitivity to various numerical parameters, and a comparison between the results generated by the fully coupled SPH-FE methodology and a strip theory method.

A naval ship, with waterline length (L_{WL}) of approximately 110 m, and length to beam ratio of approximately eight, is studied. The mass distribution is for the full scantling departure load condition, with mass of the structure plus the application of lumped masses to selected nodes to represent internal machinery, fluids and stores.

The numerical domain should conform to existing rules and guidelines to avoid the known issues with behaviours as blockage factor and wall (domain) interference [19]. The test cases, defined by the SPH particle diameter, domain width, and domain depth, are given in Table 1.

Table 1: Test matrix, all runs at ship speed (v) of 9 kn and in head seas

Run #	SPH particle diameter (m)	Domain width (m)	Domain depth (m)
1	1.2	50	10
2	1.2	50	20
3	1.2	50	25
4	1.2	50	30
5	0.9	50	20
6	1.5	50	20
7	1.8	50	20
8	1.2	25	20
9	1.2	75	20
10	1.2	100	20

For each test case, the ship heave response (y) and pitch response (p) about the centre of gravity are extracted. The non-dimensionalised heave response (y') and pitch response (p'), calculated using Equations 1 and 2 [19] respectively, are presented in the paper, where H is the wave height and λ is the wave length.

$$y' = \frac{y}{H} \qquad \text{Equation 1}$$

$$p' = \frac{p}{\frac{2\pi}{\lambda} \times H} \qquad \text{Equation 2}$$

Tools used in Validation

The results of the SPH simulation are validated against the results generated using traditional approaches:

- The quasi-static approach for the calculation of the still water and wave-induced shear forces and bending moments.
- The two-dimensional (2D) and three-dimensional (3D) approaches for calculating ship motions and responses when the ship is operating in a seaway.

The implementations of these approaches in the commercially available naval architectural tool MAESTRO 11.6.1 [20] are utilised in the present study.

Using the quasi-static assessment approach, only the hydrostatic and inertia force are considered. The centre of gravity and the centre of buoyancy of the model of a ship align vertically in the global coordinate system so that the ship is in equilibrium in heave, pitch, and roll. This allows the load distribution to be checked, and the closure of the bending moment distribution and shear force distribution is a means to validate equilibrium.

In the case of 2D strip theory, it is assumed that the body is rigid, motions are small, ship-hull sections are wall-sided, and the body has no effect on the waves. These assumptions permit the division of the submerged part of a ship into a finite number of strips. Then, 2D hydrodynamic coefficients for added mass can be computed for each strip and then summed over the length of the body to yield the 3D coefficients [21].

RESULTS AND DISCUSSION

Effect of Domain Depth

Figure 4a and b show the non-dimensionalised heave and pitch responses of the ship with varying domain depth, for a domain width of 50 m and SPH particle diameter of 1.2 m (test runs #1 to #4). Whilst the pitch varies minimally, the heave varies 30% over the studied domain depth range.

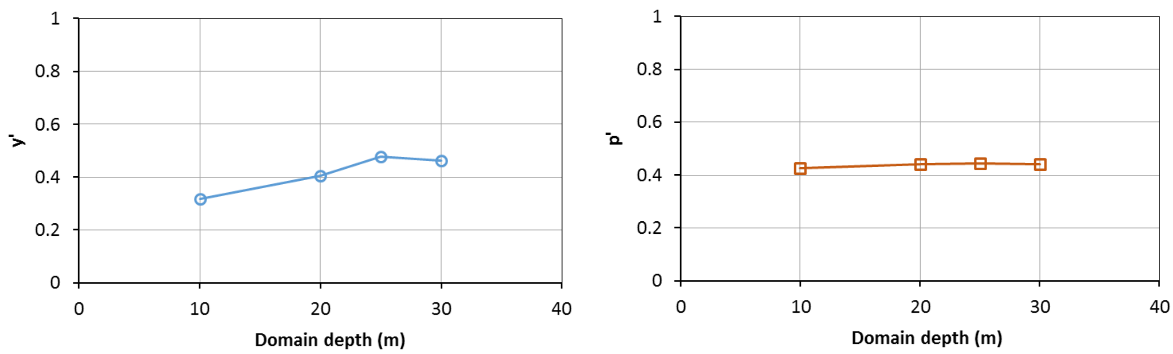

Figure 4: Domain depth versus a) y', and b) p' (test runs #1 to #4)

Effect of Domain Width

Figure 5a and b show the non-dimensionalised heave and pitch responses of the ship with varying domain width, for a constant domain depth of 20 m and SPH particle diameter of 1.2 m (test runs #2, #5, #6 and #7).

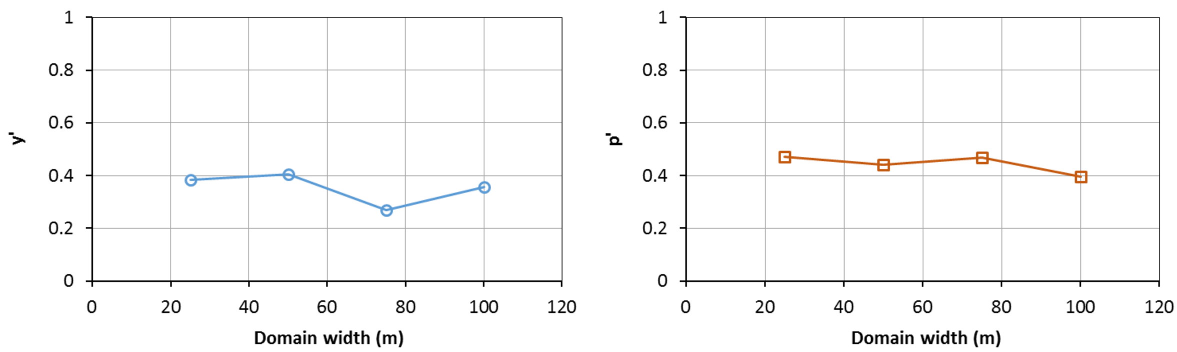

Figure 5: Domain width versus a) y', and b) p' (test runs #2, #8, #9 and #10)

Similar to that observed above, the pitch varies minimally with domain width. However, the heave response at a domain width of 75 m is relatively small. ITTC 7.5-02-07-02.1 [19] provides recommendations for dimensions to avoid tank (that is, domain) wall interference, based on running conditions. For the conditions considered, the minimum recommended ratio of domain width to model length is 1.0. Only the widest domain considered (100 m) meets this condition. This indicates that the ship response is likely to be influenced by wall reflections for the narrower domains.

Effect of SPH Particle Diameter

Figure 6a and b display the non-dimensionalised heave and pitch responses of the ship with varying SPH particle diameter width for a constant domain depth and width of 20 m and 50 m, respectively (test runs #2, #8, #9 and #10). Both the heave and pitch responses tend to be smaller when larger SPH particle diameters are used. That is, for the range of particle diameters considered, convergence (relatively small change in the motions with decreasing particle diameter) was not reached. This suggests that the SPH particle diameter should be as small as practical.

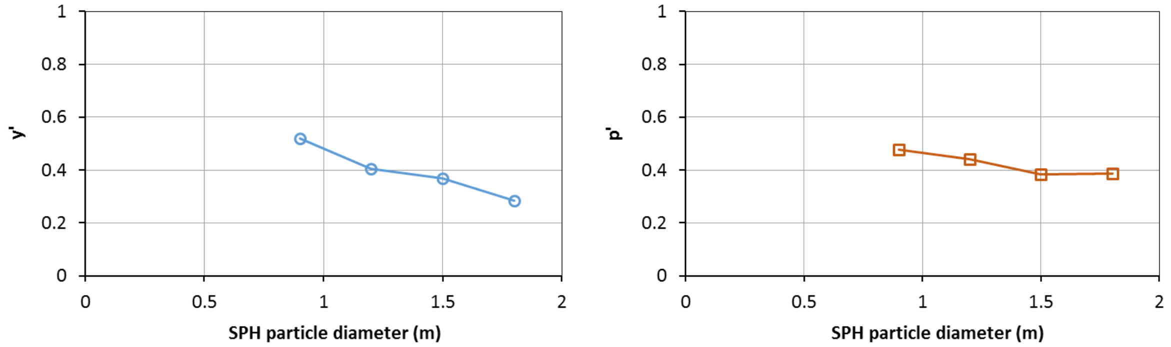

Figure 6: SPH particle diameter versus a) y', and b) p' (test runs #2, #5, #6 and #7)

Particle diameter has other influences. Larger particles have more mass, and so the interaction of each particle with the ship results in larger impact forces. This has the effect of making the interaction between the hull and the water noisy, requiring some form of filtering or smoothing. Smaller particles approach the continuum of water, and have a noticeably smoother force signal. Figure 7 demonstrates this effect where the contact force with time between the water particles and one athwartships strip of the ship for 0.9 m and 1.8 m diameter SPH particles. The 0.9 m diameter particles exhibit a less noisy force, and the ship response is smaller when larger SPH particles are used. The larger impacts from particles can also excite anomalous structural vibrations in the ship.

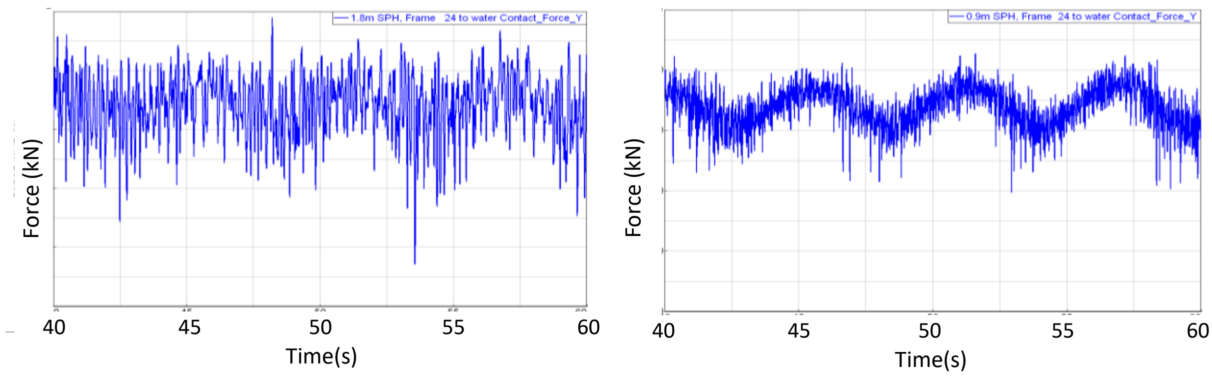

Figure 7: Time history of contact force between hull and water for a) SPH particle diameter of 1.8 m (test case #7), and (b) SPH particle diameter of 1.8 m (test case #5)

Still Water Vertical Bending Moment

VPS enables forces and moments to be extracted at sections defined within the model. There were 10 equi-spaced sections defined over a 55 m section in the centre region of the ship to resolve these forces and moments, as shown in Figure 8.

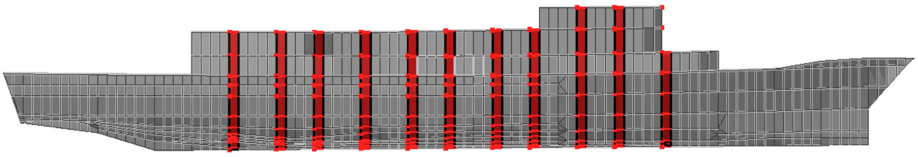

Figure 8: Location of sections for loads extraction

A comparison of the still water bending moments generated using MAESTRO and VPS is given in Figure 9. The maximum bending moment generated using VPS is approximately 11% greater than that predicted using MAESTRO. This difference is considered acceptable, as it is likely to be due to minor differences in the mass distributions between the two models. This aspect is being investigated further.

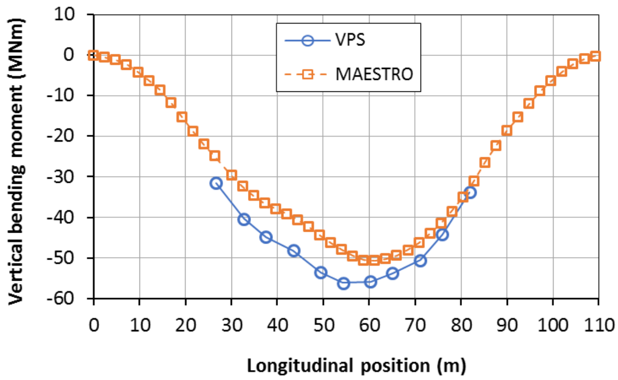

Figure 9: Still water vertical bending moment distributions calculated using VPS and MAESTRO

Vertical Bending Moment Distribution at Forward Speed in Waves

Figure 10 shows a comparison of the bending moment distribution calculated using 2D strip theory, implemented in MAESTRO, and the bending moment distribution calculated using VPS for λ/L_{wl} of 1.0, ship speed of 9 kn, wave height of 1 m, and head seas. The maximum bending moment generated using VPS is approximately 10% less than that predicted using 2D strip theory.

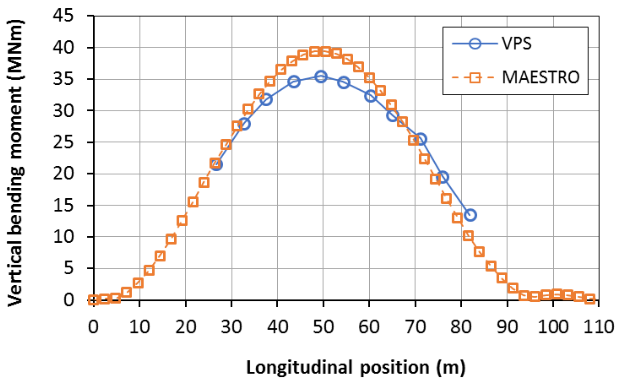

Figure 10: Vertical bending moment distributions calculated using VPS and 2D strip theory (MAESTRO), for λ/L_{wl} = 1.0, v = 9 kn, H = 1 m, and head seas

DISCUSSION

Based on the results of the sensitivity analysis, for the size of the ship, ship speed, and wave length considered, the following domain parameters are considered acceptable in terms of the accuracy achieved and computational effort required:

- Domain depth of 20 m.
- Domain width of 50 m (although best practice for experiments is 100 m, based on the result in Figure 5 the preliminary recommendation is that a domain width of 50 m provides reasonable results).
- SPH particle diameter of 1.2 m.

Based on the limited comparisons between the vertical bending moments distributions of the ship in the still water and at forward speed in regular waves, efforts to validate the proposed SPH-FE methodology are promising. Further work includes expansion of this study to other speeds, frequencies, and ship sizes.

The computer used was a 24 core Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20 GHz. The FE ship consisted of approximately 6,500 shell elements, and 15,000 bars and beams. In one example, with 552,630 SPH particles of 1.2 m diameter, filling a domain of 654 x 50 x 20 m, the simulation of 105 s of real time took 114 hours of wall clock computational time. Each SPH particle effectively requires the same computational effort, irrespective of particle diameter. Halving the diameter of the SPH particles for a specific domain size results in an 8-fold increase in the number of particles, and hence an 8-fold increase in computational effort. This becomes an important consideration in the pursuit of an economical solution.

CONCLUDING REMARKS

Based on the results of the sensitivity analysis, a domain depth of 20 m, width of 50 m, and SPH particle diameter of 1.2 m are considered acceptable in terms of the accuracy achieved and computational effort required. Further work includes expansion of this study to other speeds, frequencies, and ship sizes.

The next phase of the work in the SIoMP project is to model the degradation of the ships' structure according to ship survey reports, and compare the stresses developed in the ship in critical areas to the as-built condition. It is proposed that this approach will be effective in helping to provide more informed decisions about future or immediate repair work.

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