Study of impact loads in mooring operations using the finite element method

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Abstract

In the present work, the impact of a ship during docking maneuvers with a floating structure used in the Chilean aquaculture industry is analyzed using a structural finite element model. The commercial finite element software ANSYS, specifically its Explicit Dynamics module, is used to evaluate the effects of the collision on the fish farm structure. The geometry of the floating structure is simplified, considering only main structural components while the portion of the vessel impacting the floating system is modeled as a rigid plate to represent ship displacement and total kinetic energy. A low-velocity, high-energy impact was simulated to quantify stress distribution, deformation and energy dissipation on the system. The proposed methodology is useful for designing reinforcements on the structure, optimize fenders positions and define the appropriate ship speed in the maneuvers to prevent irreversible damage to the fish farm structure. The application of this methodology generates valuable information to improve the safety and efficiency of maneuvers between vessels and floating structures, considering the challenges that may arise during docking and load/crew transfer in protected waters. Further on-site validation of the proposed methodology is required and the use of a more complex solver to describe nonlinear behavior of structures, particularly, large inelastic deformations is proposed based on numerical results.

Key words: Floating structures, impact, docking maneuver, fish carrier ship, fish farm.

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Introduction

Over the years, the numerical analysis of ship impact on large floating structures during docking maneuvers and their consequences on the structural integrity of the platform has caught the attention of academia and industry, generating standards for the structural design of large volume offshore structures *(Storheim & Andahl, 2014)*. Of particular interest is the analysis of impacts on tubular members, similar to the ones used on floating offshore wind turbines *(Álvarez, et al., 2023)*, and SPAR platforms *(Rodríguez Morales, et al., 2025)* and the results of a sudden energy transfer over residual strength of damaged tubes, a phenomenon that is now included in multiple design standards and recommended practices common in offshore engineering *(Yu & Amdahl, 2018)*. However, there is a significant knowledge gap in the analysis of ship impacts on small volume platforms, with limited studies describing available methods to evaluate structural response of floating wind turbines subjected to ship impacts *(Ladeira, et al., 2022)*, yet describing the impact velocity as the main factor on the damage on the structure *(Ren, et al., 2022)*. The present work is focused on ship collisions on fish farms structures, light floating systems common in countries such as Norway and Chile, where the salmon farming industry represents a significant share of the national GDP *(FAO, 2024)*. The increase in vessel sizes working on fish farms creates a need for research on structural design principles that ensure the integrity of a fish farm when subjected to large energy impacts *(Yu, et al., 2019)*.

A common system for salmon farming in seawater used in Chile consists of a series of interconnected walkways made of steel rectangular tubes whose buoyancy and stability come from buoys attached to the steel structure. Walkways connected through pins form square cages of 30x30m, 40x40m and even 50x50 on arrays typically of 2x6 or 2x8 cages called a cultivation module. Alternative cages made of HDPE pipes are generally used in exposed sites; however, these represent less than 5% of the total cages in Chile. These fish farms are anchored in place by means of catenary mooring systems using drag embedment and/or gravity anchors *(Olivares, 2009)*. Integrated to the floating structure is the net system, which consists of fish nets enclosing the biomass, anti-predator nets to protect from sea lions' attacks and bird nets *(Hurtado, et al., 2018)*.

The steel walkways constitute the rigid elements of the system, their number and size will depend on the number of cages in the set or module to be installed. Its manufacture uses structural steel type A 37/24 ES and A 42/27 ES, with yield strength ranging between 235 to 265 MPa and breaking strength of 362 MPa. Regarding thickness, the most used are 4 or 5mm. Protection from the corrosive marine environment is provided by an immersion galvanizing process *(Olivares, 2009)*.

Fig. 1. Fish farm, Reloncavi Estuary, Los Lagos.

For the transfer of smolt to the site at the beginning of the cultivation process and at the end for harvesting, it is necessary to perform docking maneuvers into the cages. The mooring process of a Fish Carrier (Wellboat) involves several crucial steps that must be carried out with precision to ensure that the vessel is securely attached to the module:

a) Preparation and planning: Prior to carrying out the docking operation, thorough planning is done considering sea conditions, mainly current and wind. In addition, communication is established via VHF equipment between Wellboat and personnel at the fish farm.

b) Approach and alignment: During the approach maneuver of the Fish Carrier to the module, precise coordination is required, especially in the moment when the bow of the vessel approaches the module to enter between surface buoys of the mooring system. At this point, before starting the transverse displacement with the help of the thrusters, it is essential to achieve precise alignment between the cages and the Wellboat.

c) Speed and distance control: During the approach, speed and distance are carefully monitored. Operators constantly assess the alignment and adjust as necessary to ensure a safe connection between vessel and module.

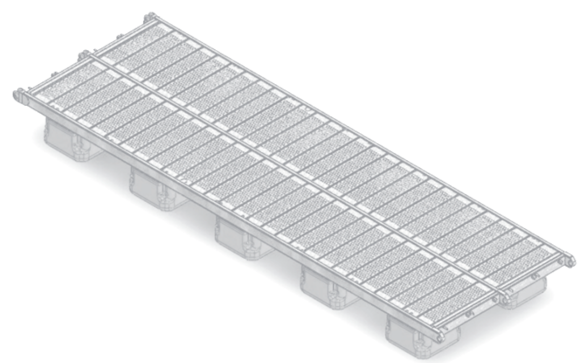
d) Hooking and verification: The Wellboat uses specific devices, such as winches, bollards and mooring ropes, to attach to anchor points on the module. The connections are thoroughly checked to ensure that they are safe and then the loading pipes are hoisted and positioned, to start the transfer of fish from cage to the vessel.

Fig. 2. Fish carrier "Cacique 1" in approaching maneuver.

Methodology

A methodology for numerical analysis using ANSYS Explicit Dynamics software for impacts between a vessel and a floating structure using as an example the case of a collision between a fish farm and a Wellboat during biomass loading and unloading maneuvers is described. Instead of considering the entire module with multiple interconnected walkways, the focus is on analyzing a single standard walkway on the center portion of a square cage (Fig. 3). This is because nonlinear behaviors such as impacts are computationally expensive in terms of computational resources, and a central walkway is the critical section during docking operations, as explained above. A full detail description of the methodology applied on this work can be found in the work by Hueichan, 2023.

Fig. 2. Central walkway on a fish farm structure (Olivares, 2009).



The geometrical configuration of the central walkway was designed based on existing fish farms and technical information from suppliers. The walkway model is composed of tubular steel tubes with rectangular cross section, while “U” shaped profiles were used for the interior reinforcements. These profiles are shown in Fig. 4and their dimensions are shown in Table 1.

For the numerical evaluation of the system, the structural model was simplified, keeping the main components which are the ones

Fig. 4. Walkway structural design.

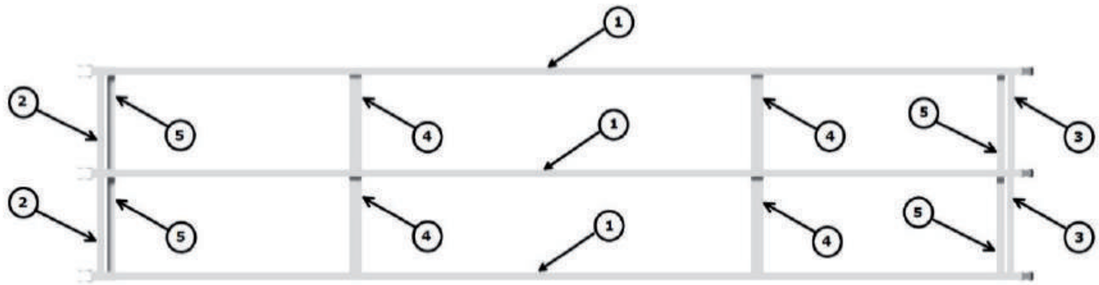


Table 1. Main structural components on fish farm structure.

Item N°	Description	Length
1	Rectangular section 200x70x5 mm	9290 mm
2	Rectangular section 200x70x5 mm	929 mm
3	Rectangular section 200x70x5 mm	953 mm
4	U section 125x50x4 mm	953 mm
5	U section 80x40x4 mm	953 mm

supporting and transferring forces from the vessel to the rest of the module. To carry out the study, the following simplifications were made:

- Non-critical elements, such as railings, floors, counterweights, and others, were eliminated to simplify the model without compromising the analysis.
- The ship was modeled as a non-deformable steel plate representing the total mass and inertia of the ship to describe collision dynamics.
- Given the nature of the joints between walkways and their horizontal displacement constraints, only one central walkway will be considered, and its representation will be carried out by the restriction of the six degrees of freedom in the nodes representing the pin connections. This decision allows us to effectively model the behavior of the central walkway structure in response to impact loads.
- Fenders were arranged uniformly along the central walkway to mitigate the impact energy and protect the collision zone.
- The model uses three-dimensional elements (bricks) to represent beams and fenders, due to numerical instabilities found when using shell elements due to the behavior of the elastomeric material on fenders.

These considerations aim to simplify the structural model without compromising the collision analysis and its effects on the central walkway, the resulting geometry is shown in Fig. 5.

It was decided to preprocess this geometry with the SpaceClaim tool available in the Workbench environment, where the model parts were labeled before editing the analysis. The material properties used in the analysis were obtained both from external references and from the material library provided by the software. Tables 2, 3 and 4 present these properties.

Fig. 5. Simplified geometry.

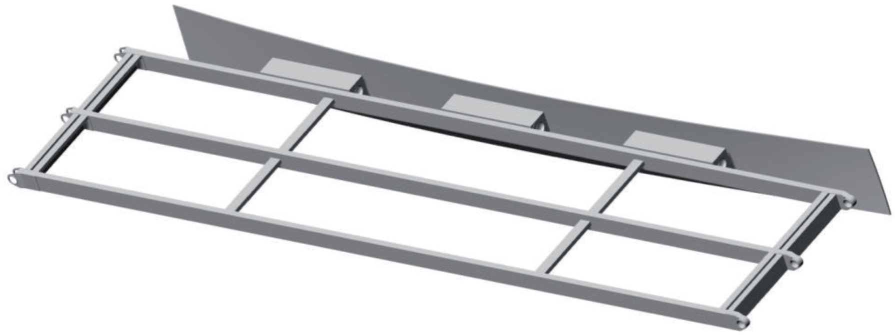


Table 2. Walkway steel properties [3].

Property	Value	Unit
Density	7800	*kg/m*³
Elastic modulus	200	*GPa*
Poisson Coefficient	0,26	--
Creep limit	250	*Mpa*
Tangent modulus	2100	*Mpa*
Breaking stress	550	*Mpa*
Maximum shear stress	320	*Mpa*

Table 3. Fender material properties [4][5].

Property	Value	Unit
Density	950	*kg/m*³
Elastic modulus	10,63	*GPa*
Poisson Coefficient	0,4698	--
Mooney-Rivlin parameter	-	-
C10 constant	0,15	*Mpa*
C01 constant	0,015	*Mpa*
Incompressibility parameter	$1{,}212 \cdot 10^{-9}$	1/*pa*

Prior to analysis, the module and fender parts were joined with a 1 mm tolerance, the vessel was close to fenders to avoid unnecessary calculations on the approach phase. A frictionless interaction between bodies was assigned and the hull was considered as non-deformable to avoid energy absorption.

It was decided to perform iterations on a simple model and by comparing results it was possible to obtain a mesh that does not represent a significant computational load, yet provides physically reasonable results, which have the following characteristics:

Table 4. Ship steel properties (LLC, 2024).

Property	Value	Unit
Volume	0.15057	m^3
Required density	1,326 • 10^7	kg/m^3
Elastic modulus	200	*Gpa*
Poisson Coefficient	0.3	--

Table 5. Mesh characteristics (Setiyana, et al., 2020) (Ansys, 2024).

Geometry	Element size (mm)	Grid
Walkway body	25	Hexahedral
Walkway connections	15	Auto
Fenders	20	Auto
Vessel	130	Hexahedral

There is only one boundary condition on the model which consists of a six degree of freedom restriction of the inner faces of the connections where pins connecting walkways are installed.

For a vessel of 2000 tons of displacement (weight), speeds to be included in the analysis correspond to typical conditions for berthing maneuvers and are presented in the following table:

Table 6. Initial speed and energy.

Case	Speed (kn)	Speed (m/s)	Energy (J)
1	0.5	0.257	66049
2	1	0.515	265225
3	1.5	0.772	595985

The parameters to be controlled for Explicit Dynamics analysis are described below:

Stage and Time Control: Short simulations of 0.5 seconds were carried out at first to observe the initial response of the model at the indicated velocities.

Solver Control: In response to variations in the execution time when calculating bending moments in linear elements, they were treated as trusses in the numerical model since no linear elements were used in the simulation. For hexahedral elements, we have chosen to use a single-point Gaussian quadrature to approximate their volumes. Although this choice may affect the accuracy on deformed elements, it offers considerable efficiency in the use of computational resources, which significantly reduces the computational time by more than 100 hours *(Ansys, 2024)*.

Damping control: In this case the use of Flanagan Belytschko method for Hourglassing control is applied. In addition, it was necessary to add a viscosity coefficient to the model for hexahedron solid elements because an oscillation occurs when the fender contacts the vessel and distorts the response of the module.

Erosion Control: Material failure representation has been incorporated. Other features, such as geometric limits and time step limits, have been kept in their default settings without additional modifications.

Results

Once analyses were performed under the configuration indicated above, the solver was executed, and results evaluated. Each simulation required approximately 62 hours of computation time. The outputs in terms of deformation, stresses and energy are detailed below.

Fig. 6 shows deformations under the load configuration for a speed of 0.5 kn. It is observed that, when placing fenders without gaps between transverse elements, the first longitudinal member of the cage undergoes substantial deformation before the load is distributed to the other fenders and cage sections. This trend remained consistent across all loading rates evaluated.

Fig. 6. Deformation of structure and fender at speed 0.5 knot.

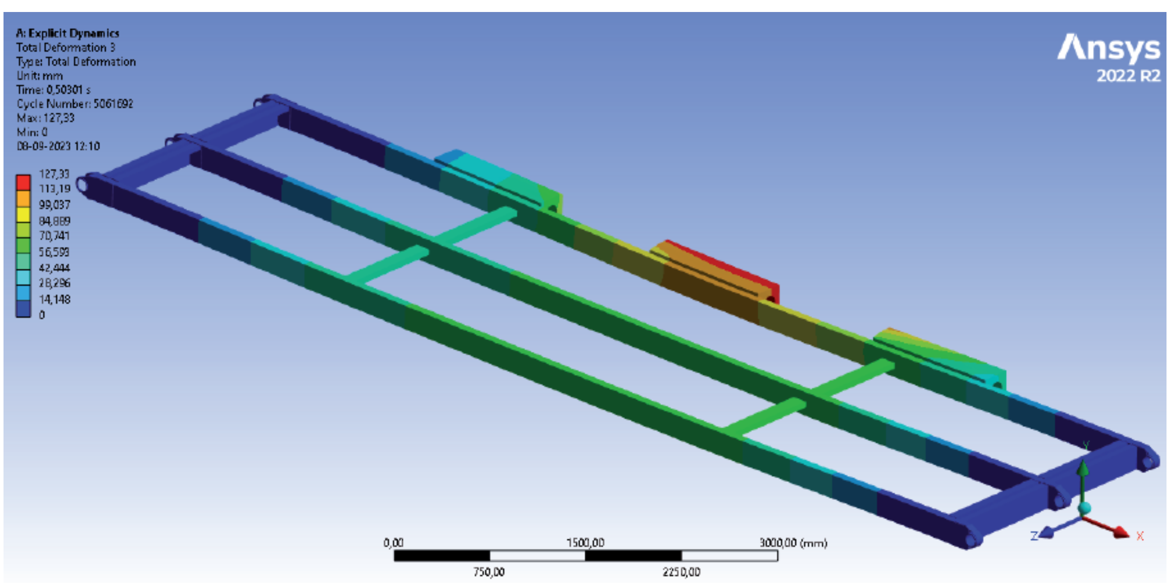
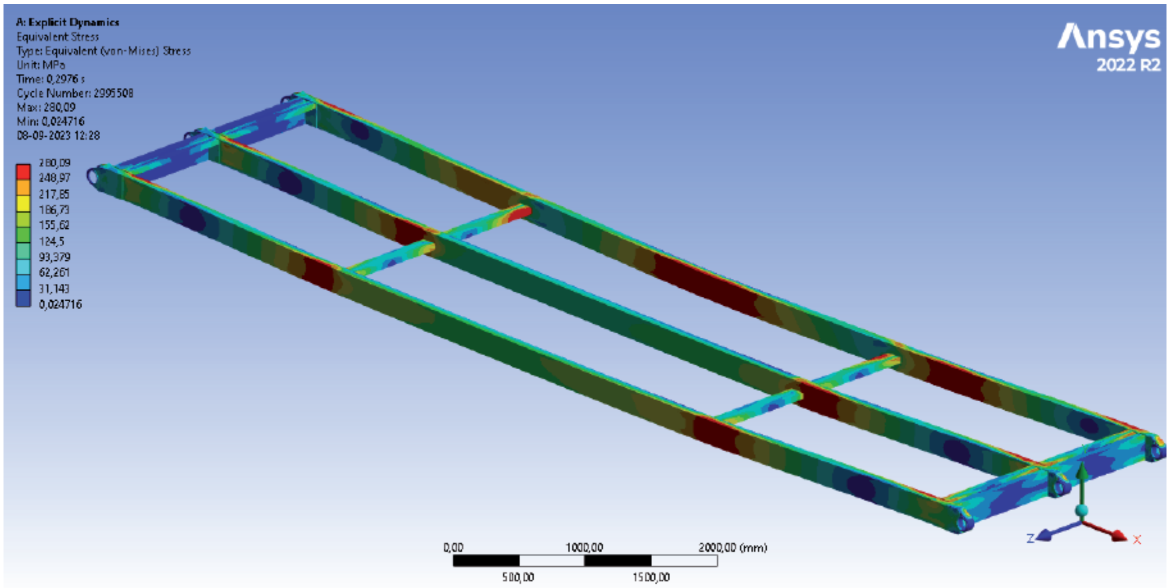


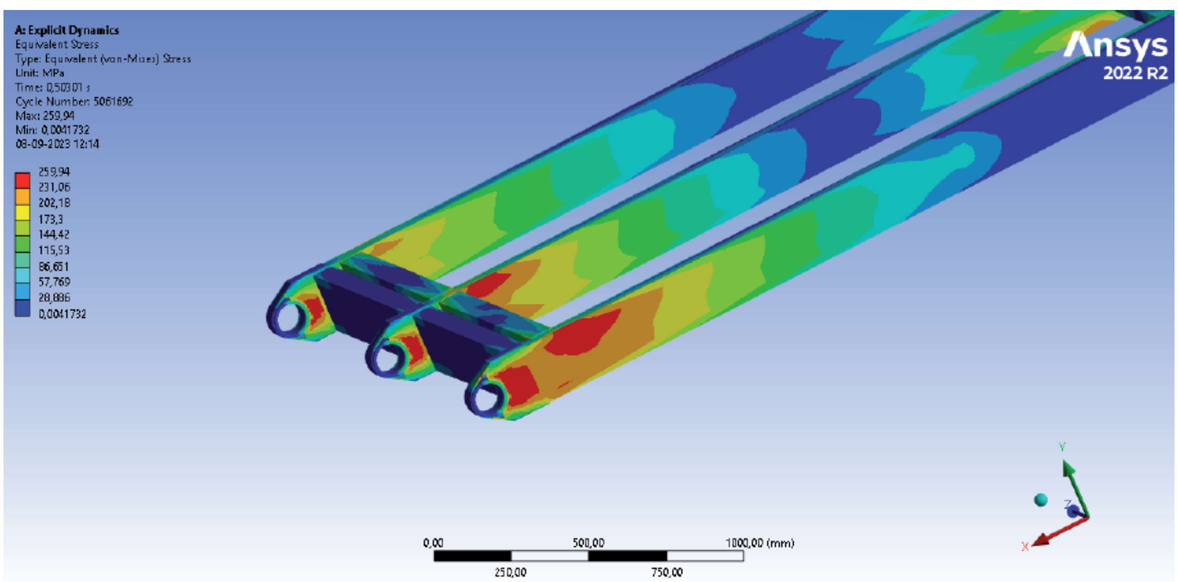
Fig. 7. Von Mises stress at 0.3 seconds at speed 1.5 knot.



As for the stresses (Fig. 7), a similar pattern to that of the deformation is observed. Stress is concentrated in the center of the longitudinal element. However, significant stresses are also identified in the contact region between the internal transverse and longitudinal structural elements. In addition, it is possible to observe that the substructure design to support pin connections is playing an effective role in absorbing these stresses, preventing them from locking the relative motion between walkways.

A localized stress was observed in the cage (Fig. 8), specifically in the forward portion of the hull (positive x-axis), due to the shape of the ship on the impact zone, this is observed across all speed conditions. In contrast, stresses in the fenders are barely perceptible due to the size of those installed in the cage.

Fig. 8. Von Mises stress at connections at speed 0.5 knot.



Moreover, since the fender material behaves practically as incompressible and no type of failure has been assigned, they will move after their initial deformation, without presenting noticeable stresses. Consequently, at the simulated speeds, the fender system was able to mitigate the impact, so the central walkway absorbs only a small portion of the impact energy.

These results indicate that the response of the fender to impact is effective. The deformation was able to absorb approximately 24% of the energy mitigated by the entire module system. These fenders, unlike a spring, serve the purpose of preserving the integrity of the cage by expanding the area of application of the impact load and preventing it from concentrating at one point.

Conclusions

In relation to the displacement (mass) of Wellboats, it is noted that even at low speeds, these vessels have considerable kinetic energy upon impact. This energy could lead to a load that exceeds the capacity of the cage, which represents a significant risk in maneuvers. Therefore, it is recommended that during the initial approach phase, strict control of both speed and distance from the fish farm must be maintained.

To address this problem, it is recommended that vessels conducting these operations are equipped with Doppler speed logs (DSL) that can detect transverse velocities, both aft and forward, relative to the water and seabed. This would allow greater control of speed and significantly reduce the risk of potentially damaging impacts during approach and mooring at farm sites (González, 2020).

Depending on the deformations obtained, the fenders should be installed in areas of the structure where transverse reinforcement connects to longitudinal. This prevents undesired deformations and guarantees an adequate distribution of stress in longitudinal members of the structure.

By using a simplified representation of a vessel, the center of mass of the vessel is omitted, so in the future it would be recommended to be able to represent it in the analysis.

In perspective, it would be advisable to explore the adoption of software that provides a higher level of control over time steps to reduce computational work. In the present analysis, time steps were automatically determined based on the smallest mesh element. In contrast, tools such as LS-Dyna allow users to manually set the time step, which provides more precise control over the solution process (Ansys, 2024). It is advisable to carry out tests on the materials to enable more accurate numerical modeling. This will ensure that the behavior of the fenders in response to loads is accurately represented in the simulations.

Contributions

- Daniel Hueichán: Writing – original draft, Validation, Investigation, Conceptualization
- Cristian Cifuentes: Writing – original draft, Writing – review & editing, Validation, Supervision, Investigation, Conceptualization
- Gabriela Martínez: Writing – original draft, Writing – review & editing, Supervision, Investigation
- Marcos Salas: Writing – original draft, Writing – review & editing, Super-vision, Investigation

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