

TRA Visions 2016

Idea Number: **L1-30**

PILLAR / TRANSPORT MODE	
ROAD ☐	RAIL ☐ MARINE ☒ CROSS MODAL ☐
Project Related to:	☐ RA1: Environment – Decarb., Sustainability & Energy Efficiency ☐ RA2: Vehicle & Vessels Technology, Design & Production ☐ RA3: Urban and Long-Distance People Mobility – Systems and Services ☐ RA4: Freight Transport & Logistics ☒ RA5: Safe, Secure and Resilient Transport Systems ☐ RA6: Transport Infrastructures ☐ RA7: Human Factors, Socio-Economics and Foresights ☐ RA8: Automation and Connectivity ☐ RA9: Enabling Environment for Innovation Implementation

Project Title:

Numerical and Analytical Simulations of Ship-Jacket Collisions

1. Introduction

Safety and reliability is the main concerned topic for every industries especially the one that are related to offshore activity. Nowadays, these activities keep actively occur due to the increasing number of offshore wind farm projects in European area which may lead to a higher probability to have a collision incident. If this accident effect has not been taking into account since in the early stage of the project, there will be a huge cost to overcome all the problems afterwards. Therefore the collision analysis become more important to ensure the safety of such operations.

The aim of this study is to validate a simplified analytical tool which has been developed by ICAM to calculate the resistance of the offshore wind turbine jackets when they get impacted by a ship. This will help the engineers to have a better judgment when working at preliminary design stage. The developed tool will be tested for several ship collision cases by modifying the impact velocity and location. Finally, nonlinear finite element analysis from LS-DYNA shall be used to validate the performance of this simplified tool. In addition, a study for validating these results with the rules from DNV-GL, BV, LR, and BSH in terms of collision analysis could be performed in order to give some recommendation afterwards.

1.1. Offshore Wind Turbines

Offshore wind turbines (OWT) has become popular in the last decade due to the fact that it has a better performance compare to the onshore wind turbine. But, it is quite challenging to build an offshore structures which are subjected to many loads such as wave, wind, potential ship impacts, and wind turbine component itself. So, there are several types of offshore wind turbine structures which mainly based on the operational characteristics and its dimension. These support structures may be defined as the Figure 1,

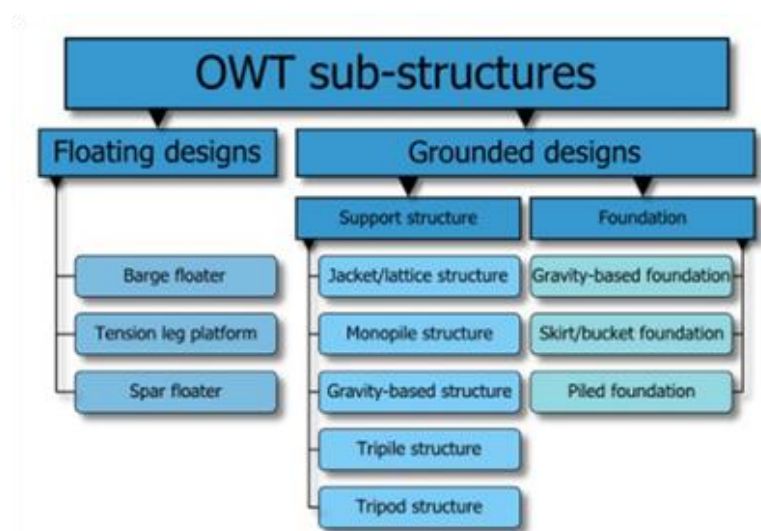


Figure 1. Offshore wind turbine sub-structures classification [14]

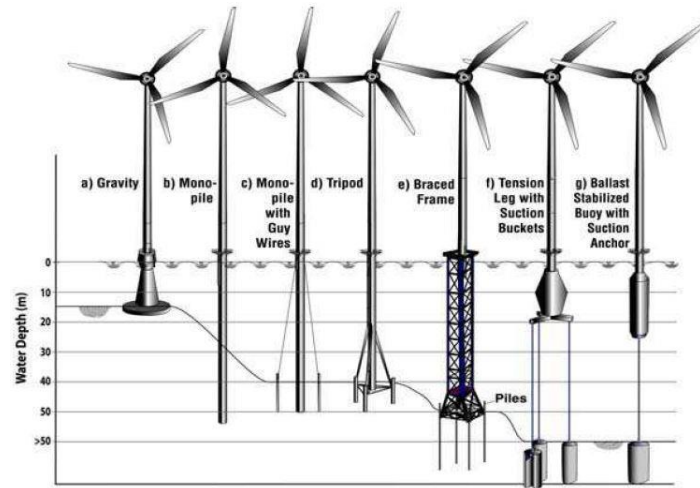


Figure 2. Commonly known OWT sub-structures [23]

As the European Energy demand by 2020, the industry should find a way to generate a higher capacity and optimal wind turbine. Nowadays, most of the offshore wind farm are using the monopole structures due to its efficiency and the water depth. But, it is not enough to achieve the target by 2020. Thus, they need to go deeper and new problem will arise in terms of the efficiency of the offshore wind turbine structures.

1.2. Risk Assessment

The demand for the energy will never end as long as the people still live in this earth. But, there is a problem on how to generate the energy by respecting the environmental conditions which has been really important in this era. The extraction of the fossil fuel always create some disturbance to its environment and the safety of the nuclear power plant brings too much risk when subjected to the natural disasters. Therefore, the idea to generate the energy with the renewable sources has become really popular in the last decade. In European Union, it is become more important since they need to achieve the targeted power capacity between 20-40 GW which shall be operating by 2020 and the planning for the following year projects had been studied as Figure 3.

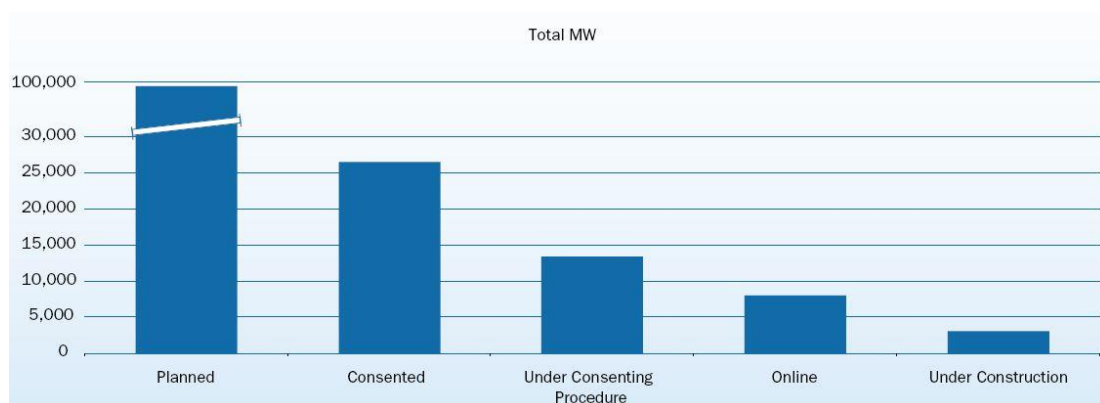


Figure 3. Offshore wind turbine markets [14]

In order to narrow down which kind of the OWT structures need to be studied, a statistical data from the European Wind Energy Association Report 2014 shows that most of them used a monopile structures. In addition, the vessel type that has a higher probability to have a collision with the offshore structures is provided. Finally, to know how important this collision need to be studied, another statistical data of collision frequency being shown here as well. All the Figures 4 below represent the fact declared above.

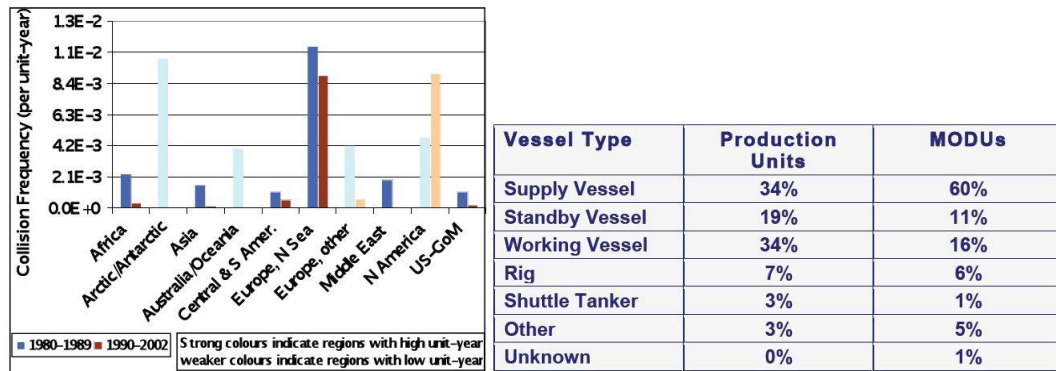


Figure 4. Collision frequency with the correspond vessel type [14], [13]

Although every approach had been taken to prevent the collision in the maritime industries by improving all the navigational technologies and create the certification from the Classification Societies for the worker, the collision incident still happened and it will have a really wide consequences as shown in Figure 5 below,

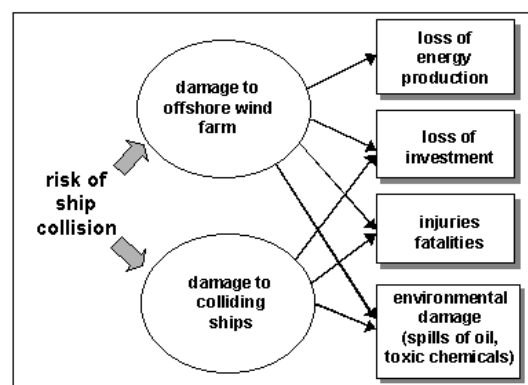


Figure 5. Classification of the ship's collision risks [25]

As we know that when a collision happen, both of the structures and ship will got damaged. Thus, which one will have a bigger damage? As we can see from the Figure 5 above that the general consequences would be loss of investment, fatalities, loss of energy production, and environmental damage. Each damages would be depend on many factors such as, wind turbine capacity, how big the ship is, how many crew on board, wind, substances inside the ship, etc. For example, a collision between supply vessel and the offshore wind turbine structures in an extreme case will cost the company hundreds of millions Euro as loss of property and energy production. Moreover, in a collision between an oil tanker and offshore structures will create a large degradation of marine ecosystem due to the oil spill on the

sea like Exxon-Valdes incident. The propagation rate of the impacted area will mostly depend on the substances itself and the environmental conditions like wind and current. Therefore, as the consequences of a collision may be very catastrophic, the research had been actively conducted in order to minimize the collision risk and damage.

There are several ways to analyzing the risk and damage from the collision incident such as: Formal Safety Assessment, Failure Mode and Effects Analysis, Hazard and Operability Study, What-If, and Fault Tree Analysis. Also, some pioneer in marine related industries had developed some collision models in order to determine the probability of the collision on sea. For example , COLLIDE (Safety Nordic AS), SOCRA (MARIN), SAMSON (MARIN), CRASH (DNV), COLWT (GL), COLLRISK (Anatec UK Ltd), DYMITRI (British Maritime Technology), and SSPA (Ellis et al, 2008). The SSPA methods is developed as the needs from the industry due to a higher sea traffic around the Offshore Wind Farms. This topic had been explained briefly by the previous work from Andres Barrera in 2013 [7].

In the other hand, the following research is an effort to develop a tool that could help people to answer the underlying question of collision, which one will received a bigger damage? The problem is there are too many collision scenario that should be analyze since the results will be different depending on the ship collision's velocity, location of impact, and type of structures. It will take a really long time to compute all this scenario by a present Finite Element Approach, therefore it is possible to develop an analytical tool that may compute such things in an efficient manner. Finally, a deeper analysis could be performed in order to develop the Classification Societies generate a new guidance to build the offshore structures or ship that satisfy the conclusion of this research.

2. Literature Survey

As the offshore activities has been increasing in the last decade, a deeper analysis regarding the collision analysis is needed in order to evaluate the collision accident that always has a negative impact afterwards. In engineering point of view, there are two ways to evaluate this problem, these method shall be explained in this part.

The characterization of the design regarding the collision phenomenon had been introduced based on the kinetic energy which basically governed by the mass of the ship including the added mass and the impact velocity. Then, this energy should dissipate into another form as the energy conservation law states. This dissipation could be explained briefly in the Figure 6.

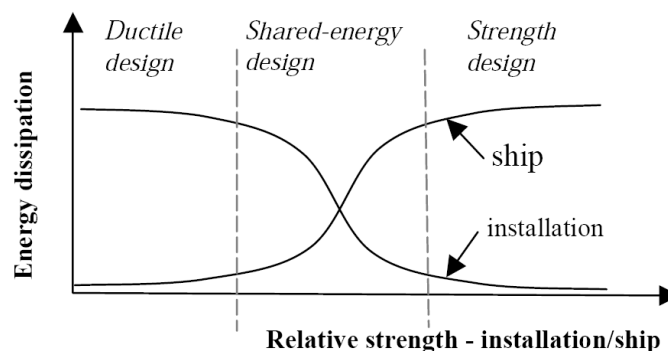


Figure 6. Concept of design against collision [20]

There are three types of the design which commonly known as Ductile Design, Shared-Energy Design, and Strength Design. The strength design means that the offshore structures is strong enough to handle the impact thus the ship will have more dissipated energy. In the other hand, the ductile design means the opposite way that the ship has a stronger structures that leads to less energy dissipation. While the combination of both design shall be called as Shared-Energy Design.

In order to assess where this energy dissipation flows, P.Visser as in Norsok Standard (2004) had established the resistance components of the fixed platforms into several types:

- Local Denting
- Elastic Beam Bending
- Plastic Bending / Hinge Formation
- Plastic Tensile Strain
- Global Deflection of the Installation
- Local Deformation of The Ship

By knowing the classification of the impact energy affecting the structures, the evaluation of the ship collision problems shall be conducted by using either the numerical method or a simplified analytical tool based on certain consideration such as accuracy and computation time.

Generally, the collision study will consist of several scenario with different parameters such as impact velocity and impact location. If the study conducted by using only numerical approach, then it will takes a longer time which is becomes the biggest problem to overcome the engineering problem. A. Bela et al [5] conducted some research about sensitivity analysis of an impacted monopile offshore wind turbine structures with different parameters such as impact velocity, wall thickness, gravity loads, wind, impact point, and soil stiffness. This analysis will become a basis for future analytical developments in order to estimate the crushing resistance and external dynamics of impacted monopile structures. The similar study also being conducted by Le Sourne et al [6] on offshore wind turbine jackets to establish the hypothesis to develop an analytical tool based on a super-element approach, this paper had concluded that the assumption of rigid striking ship is acceptable.

2.1. Numerical Method

2.1.1. General Equation

Finite-Element Method has developed into a robust and powerful tool to solve any engineering problems as the rapid development of the computing technology which starts from the introduction of the supercomputers in the 1980's. Crashworthiness analysis of every structures is one of the engineering problems that requires a dynamic analysis formulation that could be interpreted into the body movement equation as below,

$$[M + M_a]\ddot{x} + [C]\dot{x} + [K]x = F$$

Where $\ddot{x}$, $\dot{x}$, x represent the acceleration, velocity, and displacement of the nodal values vector, $M + M_a$ represent the structural and added mass matrices, C is the damping matrix, K is the stiffness matrix, and F is the total forces vector (internal and external). In general there are two methods to solve the

above equation which are implicit and explicit formulation. Each formulation has its advantages and drawbacks which makes them suitable only for certain type of problems. Thus the implicit formulation shall be used for slow-speed dynamic problems which means that the solution time spans longer than the time needed for the wave to propagate through an element. Then, the equation above will be solved by building a large stiffness matrix then inverted it to obtain the nodal displacement. It is unconditionally stable and has a bigger time step than the explicit method which requires more iterations. While the explicit formulation more useful to solve the high-speed dynamic problems that has a comparable solution time to the required time for the wave to propagate through the structure. It is conditionally stable, so there will be certain rule to decide the time step which will be explained in the following part. This equation shall be integrated using the explicit central difference scheme since the collision problem considered as a non-linear phenomenon as the internal force function (f_{int}) varies according to the displacement leading to create a nonlinear ordinary differential equations.

2.1.2. The Central Difference Method [23]

The semi-discrete equations of motion at time n are:

$$\mathbf{M}\mathbf{a}^n = \mathbf{P}^n - \mathbf{F}^n + \mathbf{H}^n$$

Where $\mathbf{M}$ is the diagonal mass matrix, $\mathbf{P}^n$ accounts for external and body force loads, $\mathbf{F}^n$ is the stress divergence vector, and $\mathbf{H}^n$ is the hourglass resistance. To advance to time t_{n+1} , we use central difference time integration:

$$\mathbf{a}^n = \mathbf{M}^{-1}(\mathbf{P}^n - \mathbf{F}^n + \mathbf{H}^n) \quad \mathbf{v}^{n+1/2} = \mathbf{v}^{n-1/2} + \mathbf{a}^n \Delta t^n \quad \mathbf{u}^{n+1} = \mathbf{u}^n + \mathbf{v}^{n+1/2} \Delta t^{n+1/2}$$

Where

$$\Delta t^{n+1/2} = (\Delta t^n + \Delta t^{n+1}) / 2$$

And $\mathbf{v}$ and $\mathbf{u}$ are the global nodal velocity and displacement vectors, respectively. We update the geometry by adding the displacement increments to the initial geometry:

$$\mathbf{x}^{n+1} = \mathbf{x}^0 + \mathbf{u}^{n+1}$$

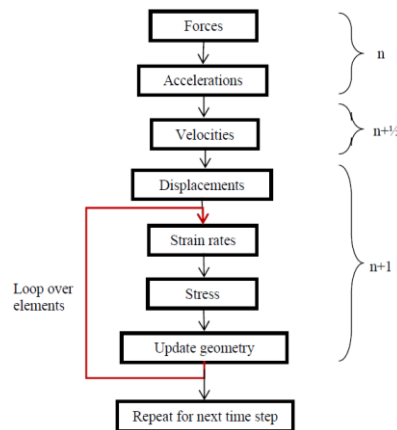


Figure 7. General central difference time integration [3]

2.1.4. Time Step Calculations for Shell Elements [23]

For the shell elements, the time step size is given by:

$$\Delta t_e = Ls / c'$$

Where Ls is the characteristic length and c is the sound speed:

$$c = \sqrt{E / \rho (1 - \nu^2)}$$

Where E is the Young's Modulus, ρ is the material's density, and ν is the Poisson's Ratio. This time step will be updated each time the element had been damaged. Thus, if the damage is too small such as cracks inside composite materials then the time step also goes smaller and leads to a really long calculation time to perform one simulation.

2.1.5. Belytschko-Lin-Tsay Shell [23]

The Belytschko-Lin-Tsay shell element ([Belytschko and Tsay 1981], [Belytschko et al., 1984a]) was implemented in LS-DYNA as a computationally efficient alternative to the Hughes-Liu shell element. Because of its computational efficiency, the Belytschko-Lin-Tsay shell element is usually the shell element formulation of choice. This element is based on a combined co-rotational and velocity-strain formulation. The efficiency of the element is obtained from the mathematical simplifications that result from these two kinematical assumptions. The co-rotational portion of the formulation avoids the complexities of nonlinear mechanics by embedding a coordinate system in the element. The choice of velocity-strain or rate-of deformation in the formulation facilitates the constitutive evaluation, since the conjugate stress is the physical Cauchy stress.

2.2. Simplified Analytical Method

2.2.1. Collision Theoretical Basis

Law of Conservation Energy states that "Energy can be neither created nor be destroyed, but it transforms from one form to another". This shall become the basis of a collision incident which explain the initial energy from a ship will dissipated to a structure in terms of internal mechanics. Therefore, an energy balance equation shall be written as,

$$E_0 = E_{int}$$

The derivation of internal mechanics needs a proper treatment and attention while the initial energy comes from the normal kinetic energy equation,

$$E_0 = 0,5 \times m_{ship} \times v_{ship}^2$$

Furthermore, Loïc Buldgen had explained in his dissertation [29] that the impacting vessel shall exerted a force on a deforming structure. Then, this force will be precisely equal to the resistance P opposed to

the penetration of the ship by equilibrium. Consequently, if V is the impact velocity, the external work rate shall be,

$$\dot{W} = P \times V$$

Which the vector V is known as the vessel is assumed to move perpendicularly to the jackets with initial velocity (V_0).

2.2.2. The Upper-Bound Theorem

A theoretical basis is needed in order to create the mathematical model of the internal mechanics. The upper bound theorem shall be used which according to Jones[24], states that *"if the work rate of a system of applied loads during any kinematically admissible collapse of a beam is equated to the corresponding internal energy dissipation rate, then that system of loads will cause collapse, or incipient collapse, of the structure"*. Thus, when the other dissipative phenomenon is neglected, the derivation of the collision resistance could be obtained by,

$$\dot{W} = \dot{E}_{int}$$

The internal energy rate is obtained by performing the integration with respect to undeformed configuration. It is intentionally performed in order to avoid a huge and complicated equations that might not be solved analytically. Then the internal energy rate for a body could be expressed as,

$$\dot{E}_{int} = \iiint_V [S] \cdot [\dot{E}] \cdot dV = \iiint_V S_{ij} \cdot \dot{E}_{ij} \cdot dV \quad \dot{E}_{ij} = \frac{1}{2} \left(\frac{\partial \dot{u}_i}{\partial X_j} + \frac{\partial \dot{u}_j}{\partial X_i} + \frac{\partial u_k}{\partial X_i} \frac{\partial \dot{u}_k}{\partial X_j} + \frac{\partial u_k}{\partial X_j} \frac{\partial \dot{u}_k}{\partial X_i} \right)$$

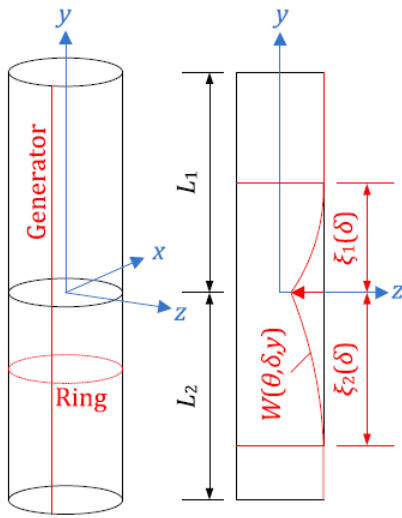
Where $[S]$ is the second Piola-Kirchhoff stress tensor and $[\dot{E}]$ is the Green strain rate tensor. A complicated equation will appear when the internal energy rate above is being evaluate with the external work rate. Therefore, some hypotheses on the material behaviour are necessary in order to make it possible to be treated analytically. These are:

- The structure is a rigid plastic material which means that the initial elastic regime is excluded based on several experiments stated in PhD Thesis of Loïc Buldgen[29]. Then, the flow stress (σ_0) is considered as the yield stress (σ_y) since working with a higher flow stress shall increase the collision resistance value which had been the primary effect by applying the upper-bound method.
- The plastic flow theory then applicable, so the internal dissipation could be evaluated with the help of Green-Lagrange strain rate ($\dot{E}_p$) as shown below (see details in [29]),

$$\dot{E}_{int} = \iiint_V \sigma_0 \cdot \dot{E}_p \cdot dV$$

2.2.3. COLEOL Algorithm

As already mentioned before that the analytical tool used here will be based on the super-elements method as had been further studied by Loïc Buldgen et al [4]. The general principles of this method is that dividing the full-structure into several sub-structures and then generate the mathematical model to represent the interaction of it. Therefore in this particular study, the jackets shall be divided into three super-elements which are impact on the vertical cylinder, impact on the horizontal cylinder, and impact on the oblique cylinder. In order to obtain the local and global crushing resistance of each super-element, the deformation mechanism and displacement field should be evaluated first. Based on the works of Wierzbicki and Suh [27], the impacted cylinders is composed of a generators supported by independent rings that are free to slide on each other without shearing as in Figure 8 below. Then the total energy rate of the crushing mechanism will be governed by,



$$\dot{E} = \dot{E}_r + \dot{E}_g$$

Where:

$\dot{E}_r$ is the energy rates of the rings

$\dot{E}_g$ is the energy rates of the generators

After some derivation as in research conducted by Loïc Buldgen et al [4], then the total energy rates is,

$$\dot{E} = \dot{E}_b \frac{\xi_1 + \xi_2}{2} + \left(\frac{1}{\xi_1} + \frac{1}{\xi_2} \right) \dot{E}_m'$$

Figure 8. Cylinders rings and generators [4]

But for the last super-element on oblique cylinder, it is difficult to derive the deformation and displacement field during the collision process, the main reason is the fact that the rings have an elliptic shape which make it harder to be imagined how the deformation looks like. Therefore, the corresponding crushing resistance shall be evaluated by using a linear interpolation between the other solutions as depicted after Figure 11,

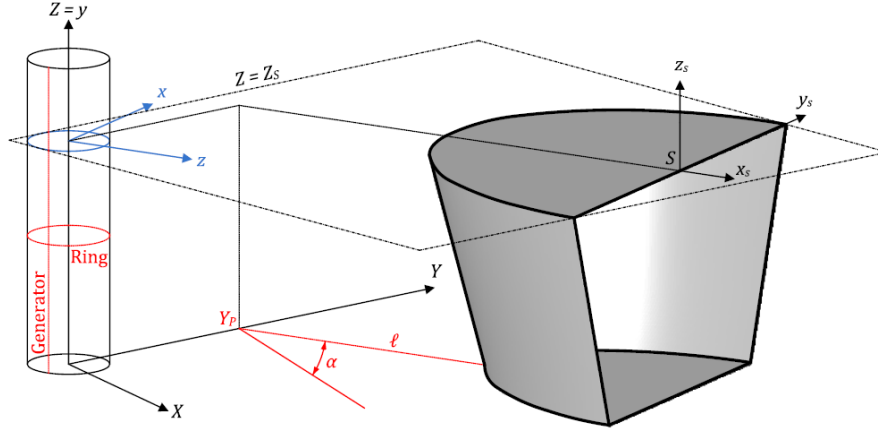


Figure 9. Impact on vertical cylinder[4]

$$P_l(\delta)\dot{a}(\delta) = \dot{E}_b \frac{\xi_1 + \xi_2}{2} + \left(\frac{1}{\xi_1} + \frac{1}{\xi_2} \right) \dot{E}'_m \leftrightarrow P_l(\delta) = \left(E_b \frac{\xi_1 + \xi_2}{2} + \left(\frac{1}{\xi_1} + \frac{1}{\xi_2} \right) \dot{E}'_m \right) \left(\frac{\partial a}{\partial \delta} \right)^{-1}$$

$$P_g(\delta) = \frac{L_1 + L_2}{L_1 L_2} \left((1 + \xi_t) M_0 \left(1 - \frac{N(\delta)^2}{N_0^2} \right) + N(\delta) (\delta - \delta_t) \cos \gamma_t \right)$$

$$\text{with} : N(\delta) = \min \left(\frac{N_0^2 (\delta - \delta_t) \cos \gamma_t}{2(1 + \xi_t) M_0} ; N_0 \right)$$

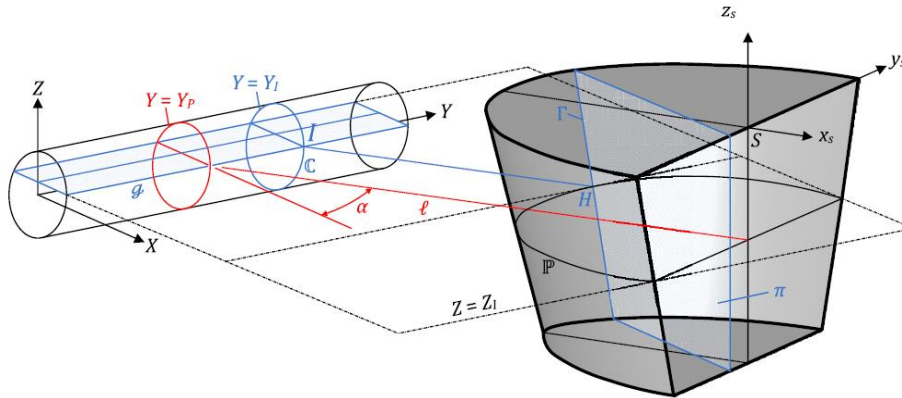


Figure 10. Impact on horizontal cylinder[4]

$$P_l(\delta)\dot{a}(\delta) = \dot{E}_b \frac{\xi_1 + \xi_2}{2} + \left(\frac{1}{\xi_1} + \frac{1}{\xi_2} \right) \dot{E}'_m \leftrightarrow P_l(\delta) = \left(E_b \frac{\xi_1 + \xi_2}{2} + \left(\frac{1}{\xi_1} + \frac{1}{\xi_2} \right) \dot{E}'_m \right) / \sin \beta \cos \alpha$$

$$P_g(\delta) = \frac{L \sin \beta}{l_1(\delta) l_2(\delta)} \left(M_0 (1 + \xi_t) \left(1 - \frac{N(\delta)^2}{N_0^2} \right) + N(\delta) (\delta - \delta_t) \cos \alpha \sin \beta \right)$$

$$\text{with} : N(\delta) = \left(\frac{N_0^2}{2(1 + \xi_t) M_0} \frac{(\delta - \delta_t) \cos \alpha \sin \beta}{2} \right) \left(1 + \frac{l_1(\delta) l_2(\delta) L}{l_1(\delta) l_2(\delta)^2 + l_2(\delta) l_1(\delta)^2} \right)$$

$$l_1(\delta) = Y_l - \delta \sin \alpha \quad ; \quad l_2(\delta) = L - Y_l + \delta \sin \alpha$$

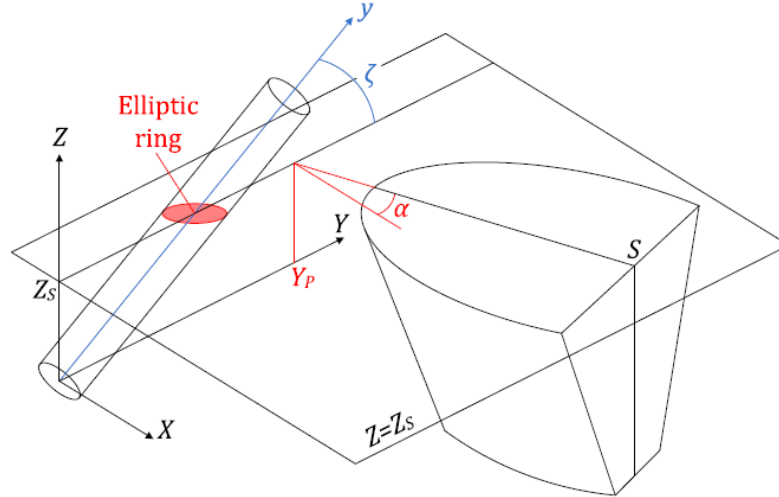


Figure 11. Impact on oblique cylinder [4]

$$P(\delta) = \left(1 - \frac{2\xi}{\pi}\right) P_h(\delta) + \frac{2\xi}{\pi} P_v(\delta)$$

Initially, the collision energy will be transferred into the localized indentation of the tube. But then, after certain penetration the tube will be forced into an overall bending motion. It means the deformations starts to affect the entire structure not only the localized near the impact point. This transition is quite smooth in the reality but not in this mathematical model because the activation of the global mode merely based on particular value of the penetration,

$$P_v(\delta) = P_l(\delta) \quad \text{if } \delta \leq \delta_t \quad ; \quad P_v(\delta) = P_g(\delta) \quad \text{if } \delta > \delta_t$$

In addition, COLEOL shall determine the state of the impacted element whether it is destroyed or only impacted by the ship's bow. Normally, we define the failure strain of a metal material as 25% which means if the length of the element increase as much as 25% from the initial length, then the element considered as a destroyed element.

There are three main things from the research of Buldgen et al (2014). First, their approach is not able to account for the displacements affecting each node of the wind turbine support, it could be updated by using Paik's approach for stiffened plates (Paik, 2003). Second, the ground flexibility should also carefully investigated since in the reality it does not have an infinite rigidity. Last point is that the effect on actual vessel strength because assuming the vessel is perfectly rigid considered as conservative way. Afterwards, Le Sourne et al (2015) conclude that "clamped leg" assumption is acceptable. This research was conducted in order to determine the hypothesis of an analytical tool (COLEOL) based on super-element method. Globally, this study has a really close relation between the conducted research papers as mentioned all above. Therefore, the corresponding paper shall be studied in order to understand all the derivation of necessary equations.

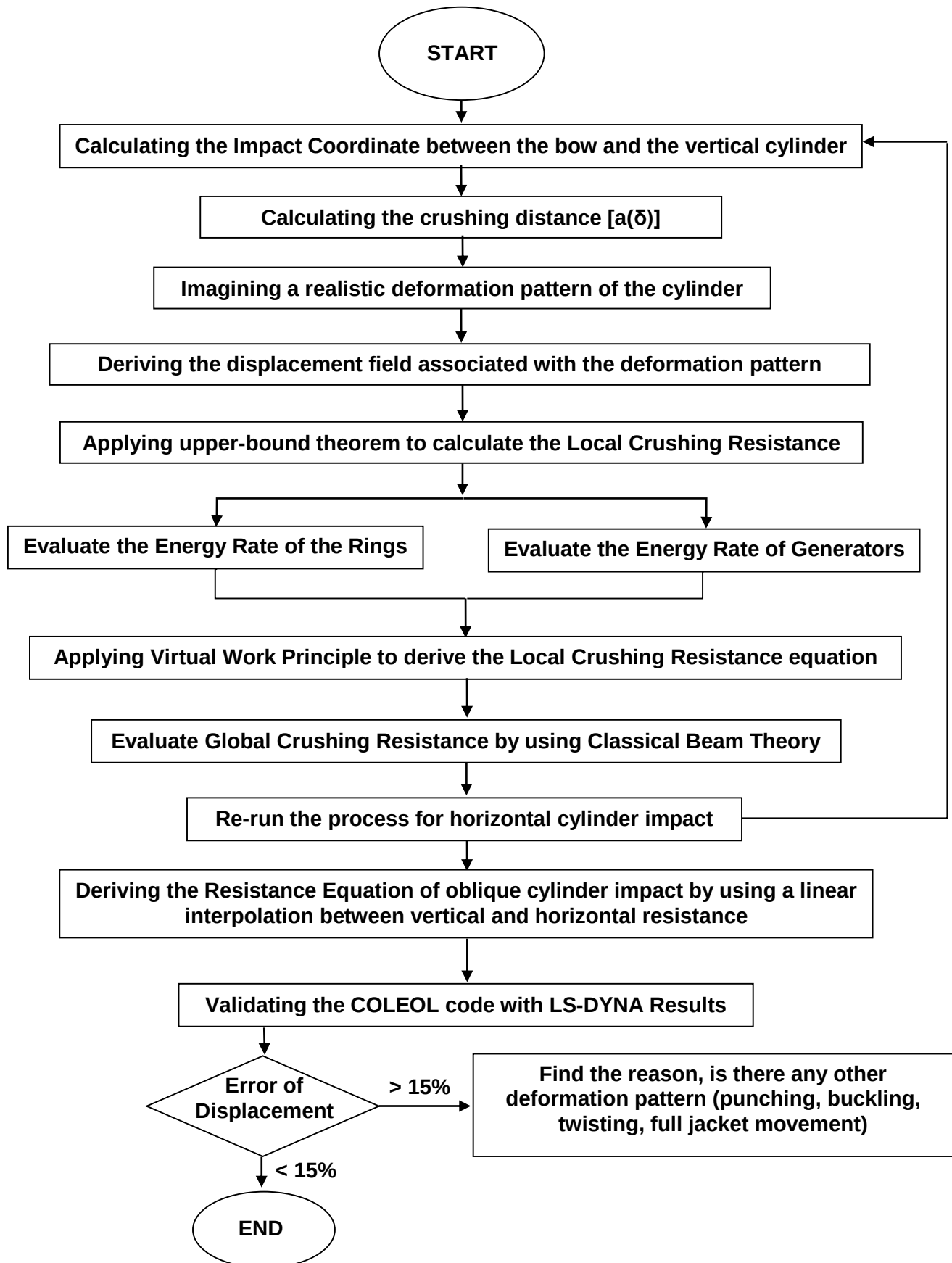


Figure 12. Flowchart to build and validate COLEOL program

3. Detailed design description

There are several items that need to be prepared in order to have a manageable results from LS-DYNA or COLEOL computation. In LS-DYNA, the keyword file (.k) is the essential file that represent the whole impact simulation regarding the material definition, inertia, speed, etc. While for the COLEOL, it needs three essential files which are the Project1.shp, striking1.xml and STXJacketsZeroML1.xml. The detailed explanation on each files shall be found on the following part. Nevertheless, the information regarding the 3D Model shall be expected as well in the following paragraph.

3.1. OSV and OWT-Jacket Model

These models have been developed and used in the previous studies performed by ICAM in the framework of work package 1 of CHARGEOL project. The jacket and the OSV bow have been meshed using Belytschko-Lin-Tsay reduced integration shell elements. In this study, the OSV is considered as a rigid ship since current version of COLEOL program only handles rigid striking ships. A punctual mass has been used to represent the wind turbine and the tower attached to the transition piece. In order to have the flexibility of changing the collision scenario, the center of gravity of the OSV could be defined inside the keyword file.

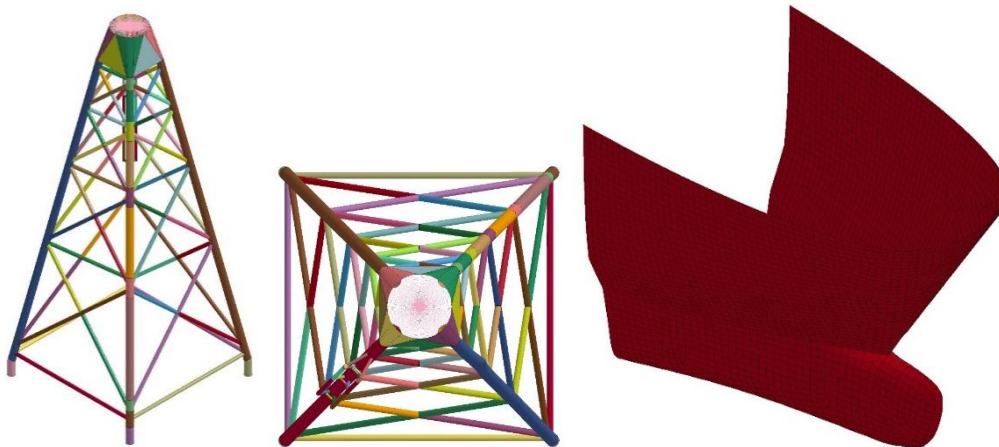


Figure 13. OWT Jacket & OSV model

Jacket Particulars				
Dimensions			Model	
Height	63,7	m	Number of Elements	300183
Width	25	m		
WaterLine	34	m	Number of Nodes	241200
Leg OD	1,22	m		
Brace OD	0,61	m	Element Size	100 mm
Leg Thickness	50	mm	Element Type	B-T Shell
Brace Thickness	50	mm		
Weight	540	Tons		

OSV Particulars		
Length	102,4	m
Breadth	23,23	m
Depth	25,89	m
Draft	4,117	m
Displacement	5000	tons
Added Mass	250	
Element Size	65	mm

3.2. COLEOL Input Item

3.3.1. My_Collision.shp File

This is the file that contain the specification of impact coordinate, angle, and speed. The coordinate should correspond with the coordinate of the My_jackets.xml file and COLEOL reads the angle in a clock wise manner and speed in m/s. A proper attention should be notified regarding the location of the corresponding file such as materials.xml, striking.xml, and My_Jackets.xml. These files should be located inside the same folder with the application (COLEOL.exe) since the COLEOL program has not been designed in a proper user interface. Therefore, do not forget to check the striking and jacket files location which is specified in this project file

3.3.2. Materials.xml File

The function of this file is to specify the material characteristics of each element that shall be used to generate the Jackets with several super-elements. These characteristics are Young's Modulus (E), Poisson Ratio (ν), Flow Stress (σ_0), and Failure Strain (ϵ_c). In this application, there will be two type of material characteristics which is sufficient to generate the OWT Jackets which named as Steel Braces and Steel Leg element.

Material Characteristics	Value	Unit
Young's Modulus (E)	2.1 E+11	Pa
Poisson's Ratio (ν)	0.3	-
Flow Stress (σ_0)	2.35 E+8	Pa
Failure Strain (ϵ_c)	0.25	-

3.3.3. Striking.xml File

This file defines the geometry of the ship bow that will impact the OWT jacket. It contains several item that correspond to the dimensions of the ship bow and, for a bulbous bow, to the dimensions and location of the bulb, as shown in figure 14 below.

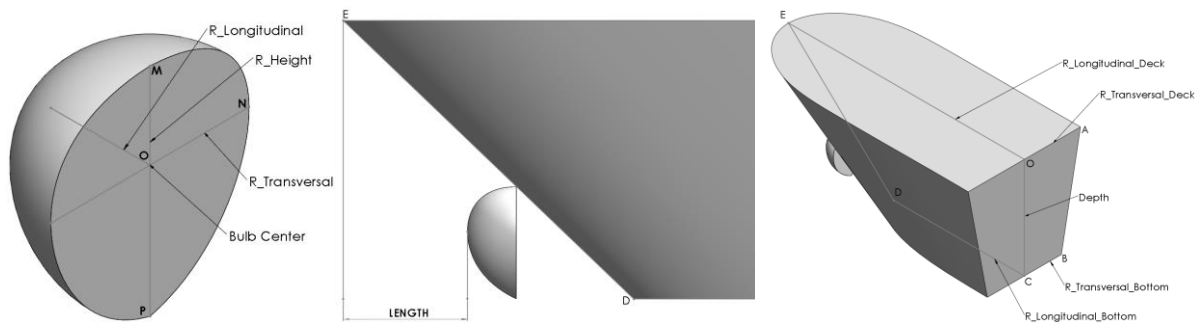


Figure 14. Striking ship in COLEOL

3.3.4. *My_Jackets.xml File*

This file describes the scantling of the OWT jacket. It is created from the connection's coordinate of all the braces and legs. Beam super-elements are defined between 2 connection nodes. Usually, companies like STX only work with a 3D CAD model which is further used to create a 3D shell elements mesh. In this case, it is necessary for the COLEOL user to have a file converter from a finite shell element mesh into this .xml file. In addition, the jacket's draft and soil connectivity (all nodes that connect the jacket with the sea bed) should be defined in this file as well. The detailed explanation of how the author built the converter could be seen inside chapter 10. An example of such conversion shall be seen in figure 15 below:

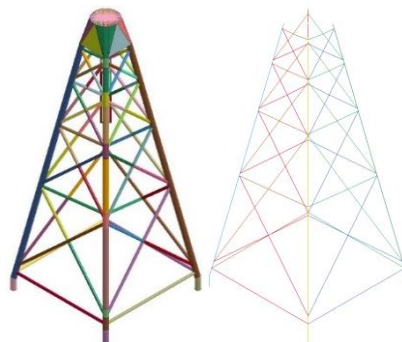


Figure 15. Jackets inside COLEOL program

3.4. **Collision Scenario**

In general there are three different collision scenarios and each of them has one varying parameters. The first scenario shall be used to investigate the effect on varying impact speed at the same impact location and impact angle. Then, the second scenario will explain the effect of varying impact angle at the same impact speed and location. Finally, the third scenario shall investigate the collision between three different locations. A better representation of the scenarios is presented as below:



1st Scenario

First Impact Location

&

90° Impact Angle

WITH

Different Impact Speed

(0.5, 1, 2 m/s)

1 2 **3**



2nd Scenario

First Impact Location

&

2 m/s Impact Speed

WITH

Different Impact Angle

(45°, 60°, 90°, 120°, 135°)

4 5 **3** 6 7



3rd Scenario

90° Impact Angle

&

2m/s Impact Speed

WITH

Different Impact Location

(First, Second, Third)

3 8 9

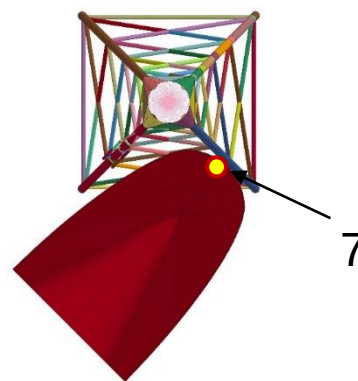
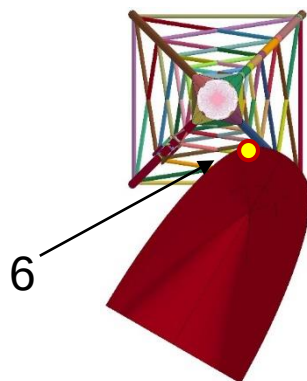
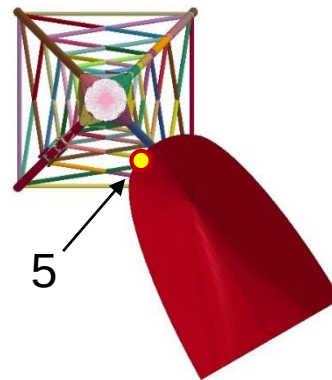
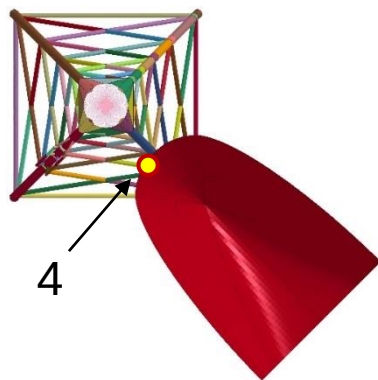
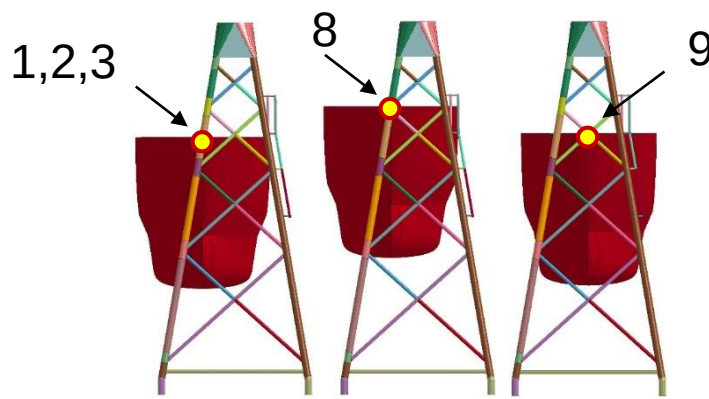


Figure 16. Collision impact scenarios

4. COLEOL and LS-DYNA Comparison

The results of the resistance and internal energy will be displayed as a function of indentation as could be seen below,

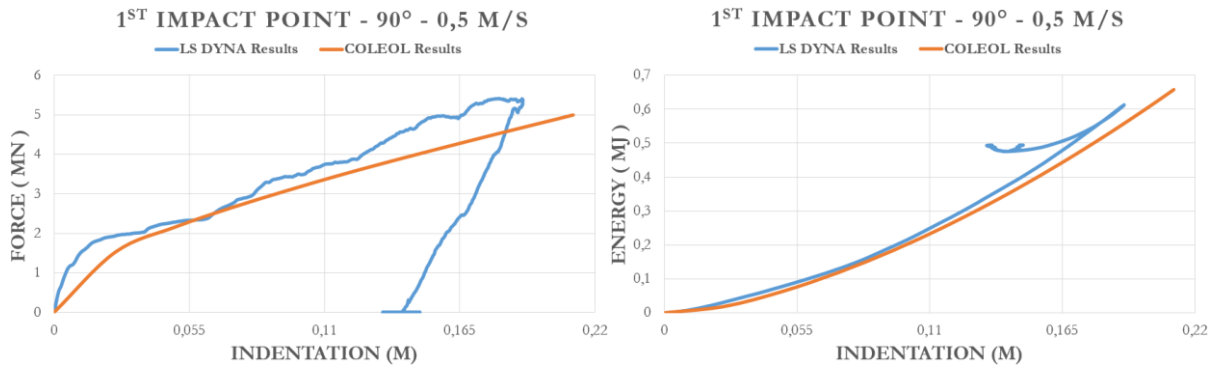


Figure 17. Test 1 results

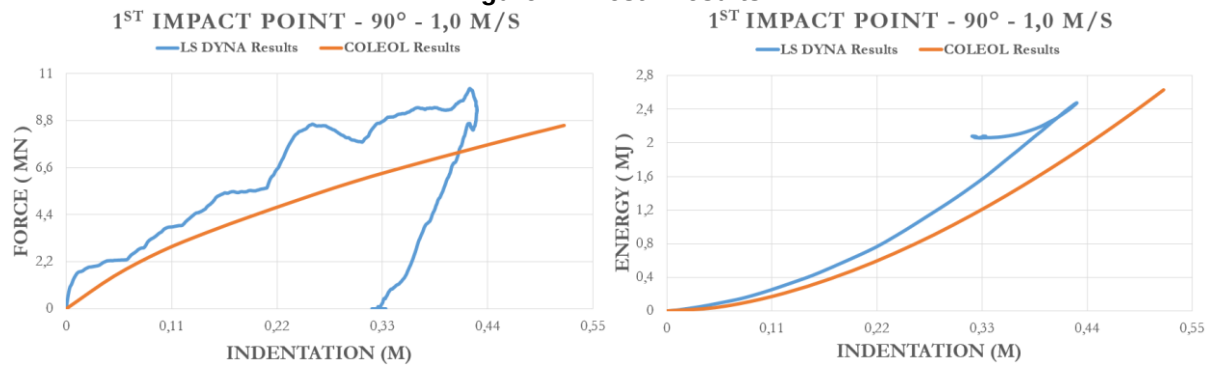


Figure 18. Test 2 results

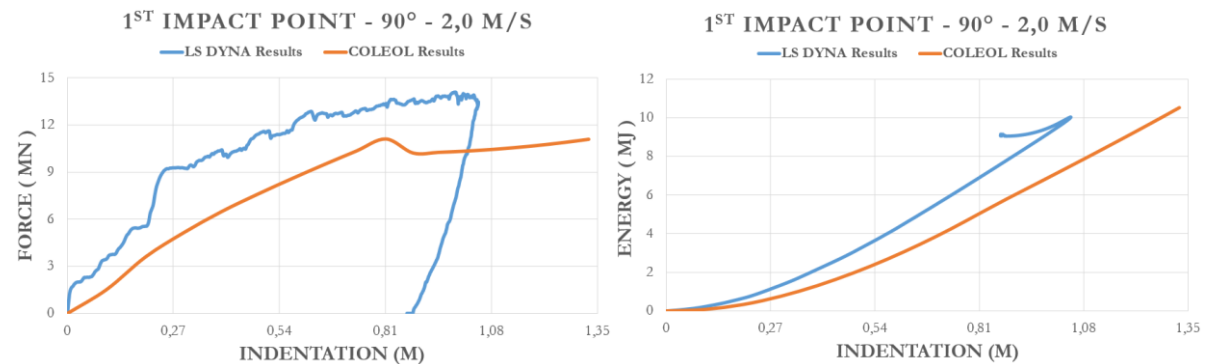


Figure 19. Test 3 results

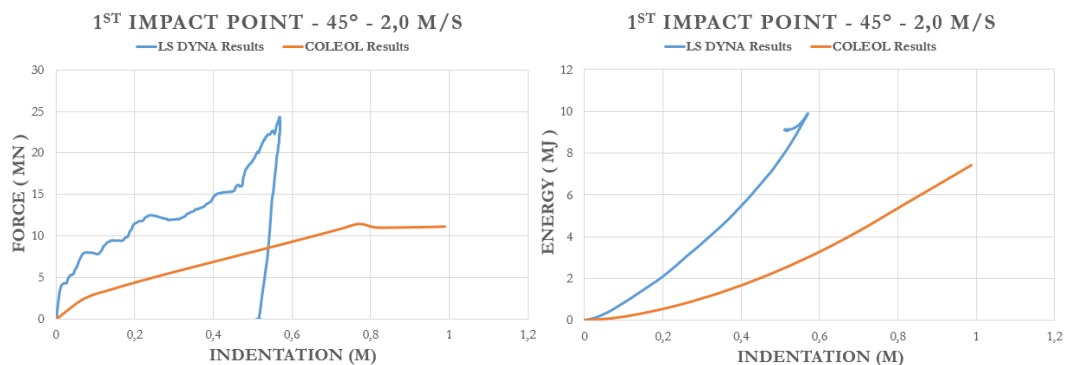
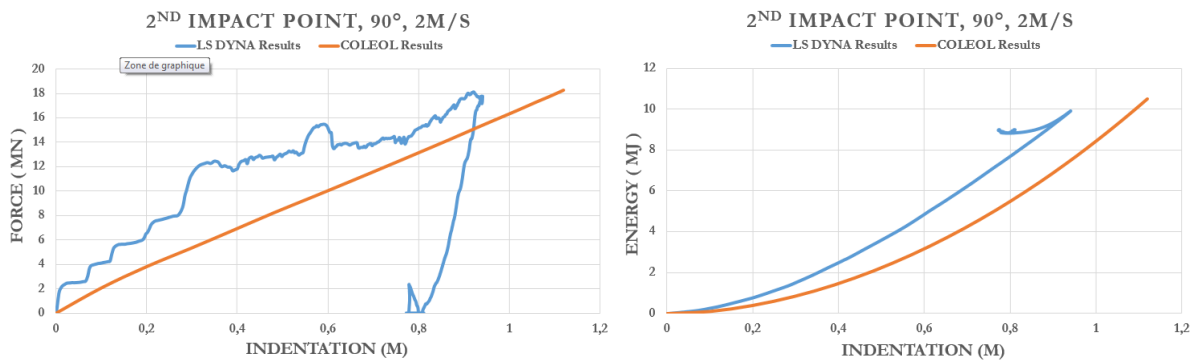
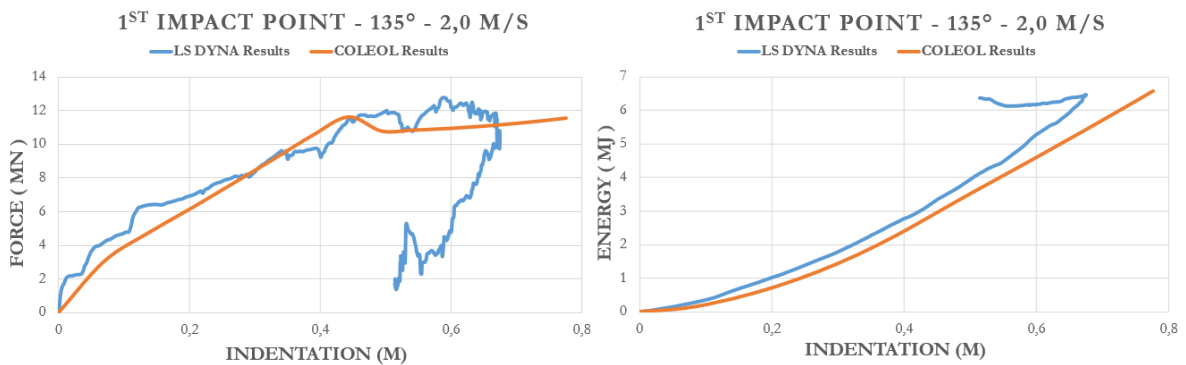
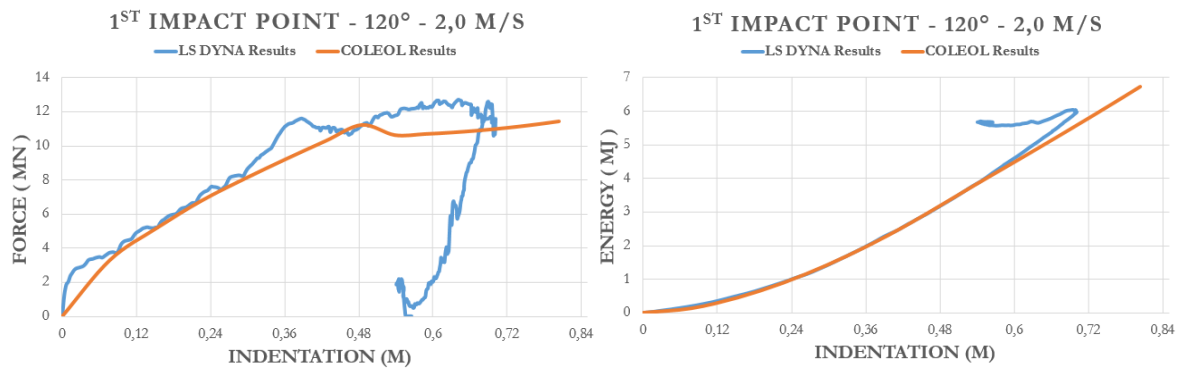
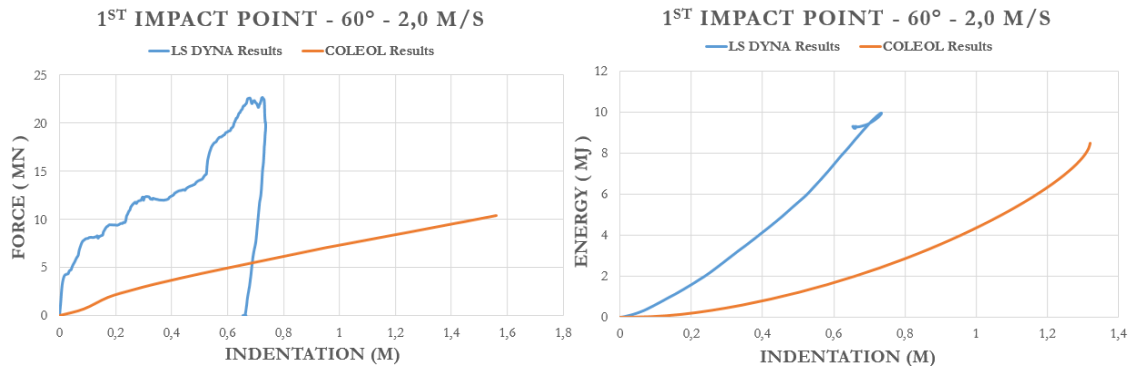


Figure 20. Test 4 results



5. Conclusion & Discussions

Based on the validation results, it is clear that COLEOL could give a good approximation results of several occasions. The selected margin of indentation's discrepancies is between 15-20% which is the same margin as in SHARP program. So, as can be seen in the table below that in the first scenario, the error is increasing as the impact speed goes faster. While in the second scenario, it is concluded that test 4 and test 5 are not able to give an acceptable results since it has the impact with the bulb. Moreover, test 9 also could not complete the calculation since there is a remaining problems inside the program. Therefore, a further improvement of COLEOL program shall be done as explained afterwards.

Scenario	Results	Error of Indentation
1	Event 1 (0,5 m/s impact speed)	9,53 %
	Event 2 (1.0 m/s impact speed)	17,67 %
	Event 3 (2.0 m/s impact speed)	20,94 %
2	Event 4 (45° impact angle)	42,88%
	Event 5 (60° impact angle)	53%
	Event 6 (120° impact angle)	12,97 %
	Event 7 (135° impact angle)	13,13 %
3	Event 8 (2 nd Impact Location)	16,06 %
	Event 9 (3 rd Impact Location)	Nan Error

By investigating the animation results from LS-DYNA, it is clear that the jackets is moving as a whole structure at certain test. This phenomenon have not been implemented yet inside the present COLEOL program. So, this would be one of the sources of the discrepancies between COLEOL and LS-DYNA as this movement also requires energy from the collision.

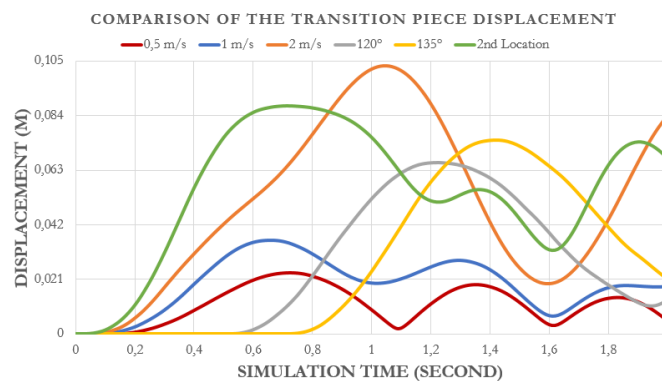


Figure 25. Transition piece displacement comparison

Meanwhile, the displacement on 120° and 135° impact angle test are quite high comparing with the others but it still has a good discrepancies with LS-DYNA results as depicted in figure 25. Thus, it is still not clear how does the graph above explain the discrepancies of the error. Therefore, a closer look on energy dissipation on the structure should be investigated in order to know how the transition piece displacement is quite high even though it has a good discrepancies.

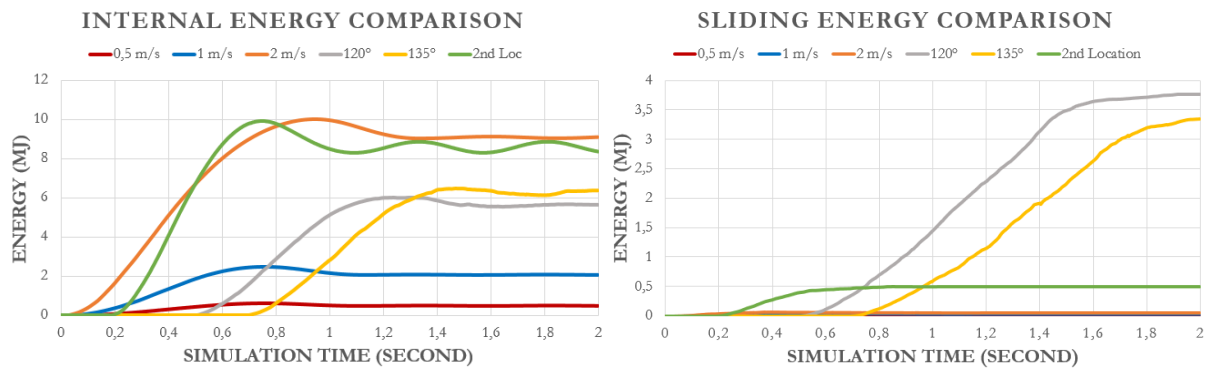


Figure 26. Internal & sliding energy comparison

Based from the energy comparison results, it is clear that the sliding energy effect may be neglected for the test 1, 2, and 3 because all the kinetic energy from the incoming ship dissipated into internal energy to deform the jackets. Also, the author believes that the occurring sliding energy on test 8 comes from the resistance of the jacket itself since the impact point directly opposed 1 leg and 4 braces. Nevertheless, the amount of it is rather small compared to the internal energy. In the other hand, test 6 and 7 have an interesting fact, that the sliding energy occur since the beginning of the impact and the amount of it are almost the half of the internal energy. That being said, it is quite logical that the sliding energy becomes the source of a high displacement on the transition piece as in figure 23. Moreover, it is important to state that the vessel is supposed to be protected from the collision accident between ship and OWT jacket. This is the idea of how the classification societies regulate the design of OSV or the jacket itself. The importance of person's life and detrimental effect to the surrounding environment has become the two main reasons to regulate such accident.

Finally, it is clear that COLEOL are able to generate a proper results with a really fast computation time compare to finite element solver (LS-DYNA). Hence, this main advantage of using analytical tool has proved that COLEOL shall be the answer to overcome the future challenge of Offshore Wind Turbine industry in terms of collision analysis. But, COLEOL is only able to predict accurately certain impact scenario which has relatively small impact energy. Thus, it is important to include all the deformation pattern that will occur during a high impact energy such as punching, buckling, shearing, and global movement of the jackets. In addition, the selection of the flow stress should be studied further since this parameter will have a significant effect on the results. The flow stress that used in this study is 2.35×10^8 Pa, while the corresponding paper from Buldgen Loïc [4] is 2.40×10^8 Pa.

In addition, the author also create a simple application for the user to be able to read COLEOL output easily. This had been done with the cooperation with STX Solutions, Saint-Nazaire. There will be three output from the simple C# application which are the time evolution of the crushing force, the absorbed energy as function of indentation, and super-element representation to notice which element is destroyed or not based on different colors. The figure 27 below will shows the result from the application.

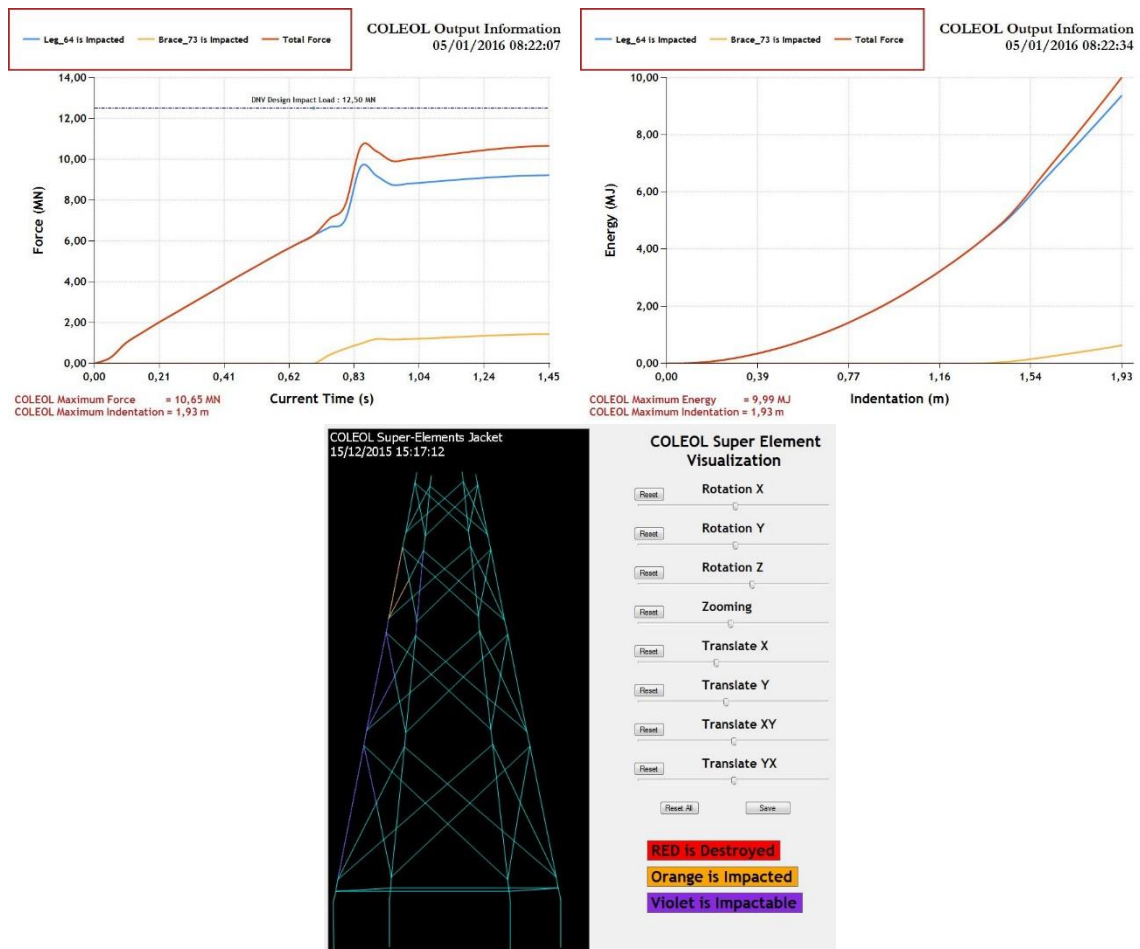


Figure 27. C# Application Results

6. Future Works

CHARGEOL is a long term project that was begun since 2 years ago. During these years, there are several researches conducted in order to develop a full working analytical code without any boundaries. This research has shown that the current version of COLEOL has certain limitations and point out the importance to implement other type of super-element especially punching deformation and also the global jacket movement patterns.

This further development had been conducted by Jing-Ru Hsieh, 2014 in order to take into account the punching and buckling phenomenon. Start from the LS-DYNA simulation as shown in figure 28 that has several deformation patterns. Then, the associated internal energy had been plotted inside the same graph as depicted in figure 29. As long as the impacted leg is concerned, the absorbed energy predicted by the super-element is in good agreement with the simulations as shown in figure 30. It is also worth noting that there are shearing deformation patterns occur near the mudline which needs more accurate prediction. Moreover, the relation between each node that governed the overall global jacket movement could be implemented based on (Paik, 2003) approach on stiffened plates. The creator of COLEOL program is optimistic that it will give a good performance as the SHARP program did to analyze the collision between ships.

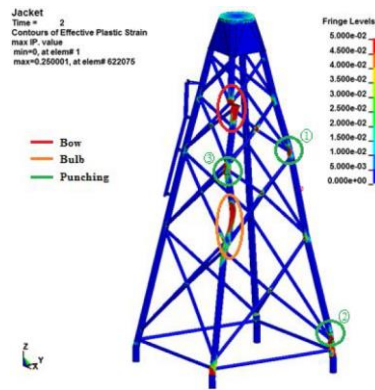


Figure 28. Simulation of high energy collision (Hsieh, J.-R, 2015)

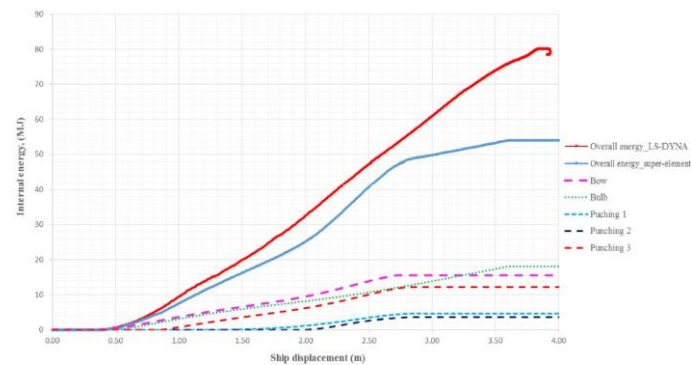


Figure 29. Overall absorbed energy between LS-DYNA and super-element (Hsieh, J.-R, 2015)

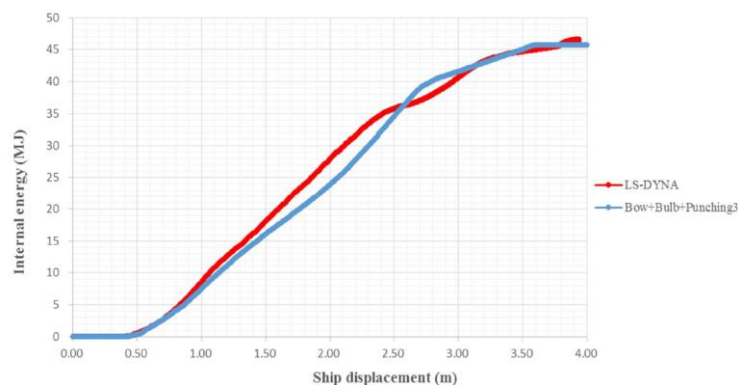


Figure 30 Absorbed energy comparison on the impacted jacket's leg (Hsieh, J.-R, 2015)

Furthermore, the proposed development has been done by (Le Sourne et al, 2016) which will be presented in the International Conference on Collision and Grounding of Ships and Offshore Structures (ICCGS 2016) in Ulsan, Korea. This development has given a really promising result with around 5% discrepancy of the crushing energy when gets impacted by 6000 tons OSV ship without the bulbous bow in 5 m/s.

7. Acknowledgements

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