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**Original citation & hyperlink:**
Orłowski, M, Bastien, C, Razmkhah, O & McCartan, S 2016, 'Design methodology for crash occupant protection in cabin design of the high speed vessel' Marine Structures, vol 51, pp. 1-20. DOI: 10.1016/j.marstruc.2016.10.001
https://dx.doi.org/10.1016/j.marstruc.2016.10.001

DOI 10.1016/j.marstruc.2016.10.001
ISSN 0951-8339

Publisher: Elsevier

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# Design methodology for crash occupant protection in cabin design of the high speed vessel

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## Abstract

Expansion of marine transport and growing number of high speed vessels travelling in the neighbourhood of the coastline significantly increase the risk of the crash on the sea. Within the existing high speed craft legislations there are no regulations related to prediction of the vessel occupants injury and trauma. Former research has exposed the similarities between the high speed vessel crash and automotive collision enabling the transfer of advanced crash safety technologies between the automotive and marine.

This paper investigates the application of the most recent CAE automotive safety technologies to predict the injuries of high speed Cruise Logistics Ferry (CLF) occupants in 40 knots crash with a harbour peer. At first, the probability of occupant injuries was studied using a 50th percentile HYBRID III standing crash test dummy model. The study considered various occupant positions within the boat cabin for two different cabin orientations. The investigation was then followed by computer analyses utilising the state of the art Total Human computer Model for Safety (THUMS) to evaluate the localised passenger traumatology. This model is the most advanced human computer model available, capable of computing injury risks at organ levels.

Results from the analyses using both models showed that the standing HYBRID III dummy was suitable to assess the overall risk of occupants' injuries in a cabin design context, while the THUMS model added detailed trauma injuries for selected occupant locations. The results of both investigation indicated very high risk of life changing injuries or even death to the boat occupant within the cabin.

A strong relationship between the probability of severe injury and the distance between the passenger and any obstacle in the cabin was found. In conclusion, the research is proposing a design methodology for cabin occupant protection based on the location of each individual passenger relative to obstacles and the associate risk of injury. This is in stark contrast to the general design guidelines of the High Speed Craft code (2000) which are based on threshold values of a global collision design acceleration.

***Keywords:***

Safety, finite element, human model, THUMS, HYBRID III dummy

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## 1. Introduction

Severe crash incidents on the sea do not happen very often. However, when they do happen they include very high number of fatalities. History of "on the sea" collisions, which include ship to ship (RMS Empress of Ireland (1914), SS Andrea Doria and S Stockholm (1956), MV Dona Paz (1987)), ship to iceberg (RMS Titanic (1912)), and finally ship to shore collisions (9 ships of US navy (1923), Costa Concordia (2012)), shows the substantial danger to human lives closely related to the crash accidents [1]. With increasing interest in the leisure marine and need for high speed freight the risk of the potential crash on the sea increases significantly. In order to allow passengers a safe evacuation two conditions need to be fulfilled. The first is the vessel integrity after crash, and the second, as much important as the first, is the survivability and mobility of the vessel occupants. The second condition can be only fulfilled if the risk of the injuries is as low as possible.

Accidents such as the Costa Concordia highlight the issues of structural damage due to crash impacts, either through grounding or involving other vessels. In such accidents the structural features, such as bulk heads are insufficient to mitigate the loss of hydrostatic stability due to structural buckling and failure. Vessel structural loading conditions are primarily determined from hydrodynamic loading in a range of sea states. The hydrodynamic loading does not take into account crash loadings. However, real life scenarios show that this type of loading cannot be neglected and should be considered within the design process.

According to the European Maritime Safety Agency, 1032 collisions and 1087 grounding/stranding accidents were reported between 2011 and 2014 [2]. This highlights the importance of considering crash loads in the design of marine structures. In fact, many researchers considered the crash on the sea as a significant danger to the ships and their occupants [3-5]. However, majority of the research focus only on vessels structural integrity and do not take into account the protection of occupant.

The Maritime and Coastguard Agency High Speed Craft (HSC) code (2000) [6] states that passenger craft shall be designed for global collision design acceleration ($g_{coll}$), which is determined from an empirical formula based on the following parameters: vessel displacement; hull material factor; length factor; kinetic energy. The collision design condition is based on head-on impact at a defined collision speed. The HSC only provides general design guidelines based $g_{coll}$ threshold levels as follows: design level 1 where $g_{coll}$ is less than 3; design level 2 where $g_{coll}$ is between 3 and 12. An overview of these guidelines is shown in Table 1. The MCA maintain that for a design level 2 situation if seats are rearward facing then they should be of high seat back design, and that sofas are not acceptable. In terms of passenger restraints one-hand-release safety belts of three-point type or with shoulder harness are to be provided for all seats for all craft with the $g_{coll}$ acceleration exceeding 3.

Table 1: Overview general HSC design guidelines [6]

| **Design level 1: $g_{coll}$ less than 3** | **Design level 2: $g_{coll}$= 3 to 12** |
|---|---|
| 1 Seat/seat belts | 1 Seat/seat belts |
| 1.1 Low or high seatback | 1.1 High seatback with protective deformation and padding |
| 1.2 No restrictions on seating direction | 1.2 Forward or backward seating direction |
| 1.3 Sofas allowed | 1.3 No sofas allowed as seat |
| 1.4 No seat belts requirement | 1.4 Lap belt in seats when no protective structure forward |
| 2 Tables in general allowed | 2 Tables with protective features allowed. Dynamic testing |
| 3 Padding of projecting objects | 3 Padding of projecting objects |
| 4 Kiosks, bars, etc., no special restrictions | 4 Kiosks, bars, etc., on aft side of bulkheads, or other specially approved arrangements |
| 5 Baggage, no special requirements | 5 Baggage placed with protection forward |
| 6 Large masses, restrainment and positioning | 6 Large masses, restrainment and positioning |

In terms of accommodation design the HSC code [6] states that public spaces, control stations and crew accommodation of high-speed craft must be located and designed to protect passengers and crew in the design collision condition. These spaces are not be located forward of a transverse plane, which is determined by an empirical formula for the plan projected area of craft energy absorbing structure forward of the transverse plane. The empirical formula is based upon the following parameters: total plan projected area of craft; material factor; framing factor; operational speed.

Recently, many researchers studied ship collision and grounding using the nonlinear FE analysis. These studies involved collisions between two ships [4, 7] or ships and other structures [8, 9]. However, these studies were only investigating low impact velocities, i.e. below 10m/s. In these types of impacts, the accelerations acting on the boat occupants are low and they do not impose hazard of serious injuries. Impact outcomes, however, change for high speed vessels travelling at velocity of 30-55 knots. The accelerations acting on the occupants in case of the crash are approximately 15-20 $m/s^2$ and impose significant hazard to the passengers.

Operational velocity of the CLF is designed to be close to the Euro NCAP frontal impact test speed [10], consequently automotive crash safety protocols are adequate and can be implemented into the development stage of CLF. Nonlinear FEA can be used to predict the structural loading and assess the safety of the design in terms of the occupant protection. Safety features such as crumple zones, designed to absorb the impact energies, as well as a rigid safety cell, designed to protect the occupants, could be implemented into the structure of the CLF.

In 1951, Daimler-Benz AG registered a patent [11] for the passenger car body with a passenger safety cell. This innovation is the fundamental feature of passive automotive safety to this day. Despite the initial assumptions of the automotive design engineers which thought that a body that was as rigid as possible was the best way to protect the driver and passengers in an accident. In fact the forces generated during the impact are transferred to the occupants with hardly any prior absorption.

Further development of the automotive passive safety, where the safety cell was used together with the crumple zones, led to increase of the occupant safety. Controlled body deformation at the front and rear of the passenger safety cell, enabled for the absorption of the impact kinetic energy during crash. At the same time a rigid passenger safety cell in the middle of the vehicle enclosed the occupants and protected them from the impact forces acting on the vehicle structure.

In order to facilitate direct evaluation of the risk and injuries suffered by the occupant in automotive crash, Marzougui et al. [12] developed an FE model of the full scale automotive crash test. The model consisted of a full size car, a 50th percentile Hybrid III dummy, and a driver side airbag. The FE model was used for the simulation of an NCAP full scale crash test, which involved frontal impact with a full rigid barrier at 30 mph. Further, the model was validated against the crash test data and it showed good agreement between the numerical and test data.

Teng et al. [13] examined the dynamic response of the human body in a frontal collision event and assessed the injuries sustained to the occupant's head, chest and pelvic regions. They used Kane's method to derive governing equations describing the response of the occupant. The numerical models were capable of predicting the severity of the injuries sustained by the vehicle occupant in an impact. Teng et al. [13] proposed that the multibody dynamics modeling method provides a valuable tool for engineers to study different design concepts and to evaluate the safety of vehicles at an early stage of the research and development process.

In the early 90's Ishikawa et al. [14] developed a mathematical multi-body-system model of the whole human body. The model was used to evaluate the impact response of the human body in the car pedestrian accidents and its aim was to improve the results correlation with the cadaver tests. The results of the numerical analyses performed with the proposed model were verified against the data obtained from the cadaver experiments. The following parameters were considered for the model response evaluation: impact speed, bumper height and bumper compliance. The responses from the model in various impact configurations, such as overall pedestrian behaviour, resultant head velocity, acceleration of the segments, were compared. The output parameters calculated from computer simulations with the new pedestrian model corresponded well to observations in cadaver studies and indicated its ability to analyse pedestrian kinematics in car-pedestrian accidents.

The vehicle safety and roadside safety communities utilise full-scale crash tests to assess the potential for occupant injury during collision. While the vehicle community uses instrumented full-scale crash test dummies, the roadside community relies on the Flail Space Model (FSM) and the Acceleration Severity Index (ASI) models, which are based primarily on the deceleration of the test vehicle. Gabauer and Thomson [15] investigated the correlation of these differing metrics to gain insight to potential differences in threshold occupant risk levels in the roadside and vehicle safety communities. Full-scale vehicle crash tests were analysed to compare the FSM and ASI to crash test dummy injury criteria for different impact configurations, including frontal and frontal offset crash tests. The Head Injury Criterion (HIC), peak chest acceleration, peak chest deflection, and maximum femur force were compared to the ASI, and flail space parameters [16]. In terms of the vehicle crash test injury criteria, the occupant impact velocity and ASI are found to be conservative in the frontal collision mode. The occupant ride down acceleration had the strongest correlation to HIC while the ASI had the strongest correlation to peak chest acceleration.

Considering the occupant risks and injuries, the CLF crash combines the traits of both occupant and pedestrian in the automotive sector. A vessel passenger may be seated unrestrained or might be upright and walking at the time of impact. In this scenario, the impact with a wall, table or other fixed objects would be analogous to a pedestrian being hit by a car. This results in much higher impact loading and therefore more severe injuries suffered by the occupant [17, 18]. Possible solution to reduce the severity of the injuries is implementation of the airbags, widely used in automotive, into a CLF structure.

This paper investigates the hazard imposed to the high speed vessel occupants during the crash event. Initial assessment of the injury probabilities was performed with Hybrid III dummy model and it was restricted to the head, neck and chest injuries only [19]. The innovation of this research is the investigation of the most critical case in terms of injury probability by replacing the Hybrid III dummy model with the Total Human Model for Safety (THUMS) which enabled for evaluation of the human body injuries including the internal organs. The results of this investigation highlight the risk of the occupants during vessel collision and the importance of crash consideration in the design process of large high speed vessels.

## 2. Preliminary crash assessment of the CLF

The CLF is a high speed craft of significant buoyancy travelling at 40 knots. To enhance the passenger survivability after the collision the FE crash analysis is required for the optimisation of the CLF structure and safety systems. Since the CLF is travelling at significant velocity the potential crash have many in common with the car crash incidents. Therefore, the tools successfully used in automotive industry can be applied to the boat crash scenario.


a) b)

Figure 1 a) New CLF trimaran concept, b) Preliminary structural design.

The preliminary assessment of the CLF crash performance was performed and described in details by Bastien et al. [20]. The presented design concept is a high speed vessel which aims to compete with road transport and air transport. The vessel design combines the following functions: high speed ferry as an alternative to heavy goods vehicle road transport; high speed passenger ferry as an alternative to flights; and luxury cruising cabins. The primary dimensions of the hull, hydrostatic features and load definitions of the CLF are given in Table 2 Bastien et al. [20].

Table 2 Main dimensions and service specifications of the CLF.

| **Component** | **Material model** |
|---|---:|
| **Length between perpendiculars** | 120 m |
| **Maximum total breadth** | 28 m |
| **Depth to main deck** | 12 m |
| **Full load displacement** | 2070 t |
| **Main hull L/B** | >10 |
| **Service speed** | 40 knots |
| **Side hulls displacement** | =~5% |

The structure of the considered trimaran ferry was made out of medium grade aluminium alloy. For the preliminary structural design, the hull has been split in three blocks (see Figure 1b). The first one covers the engine room section, the second one is the greatest part of cargo decks and the last one considers the slamming loads at the bow. The use of aluminium alloy required that spacing of the ordinary stiffeners and the transversal primary stiffeners were set at the distance of 400 mm and 1600 mm respectively. The CLF was designed in accordance to Lloyd’s Register rules and it fulfils all the design requirements [20].

The trimaran crash analysis was performed using an explicit finite element solver LS-DYNA. Its main application is in short duration, transient events which involves contact between multiple components. The problem studied is a stress propagation problem and requires time step integration constant based on the mechanical properties of the materials, i.e. Young’s modulus (E), Density (ρ) and Poisson's ratio (ν). In typical automotive applications, for a 0.1 s and mesh size of 1,000,000 elements, an accepted time step is between 0.8 μs and 1.0 μs. This sets a mesh average size to 5.0 mm for a structure of 4.0 m length and 2.0 m width. The dimensions of the trimaran are 130.0 m in length and 30.0 m in width, which would create a mesh beyond most computer capabilities. Therefore it was decided that an average mesh of 100 mm would be adequate to represent the trimarans collapse mode, leading to a mesh density of 5.5 million of shell elements [20].

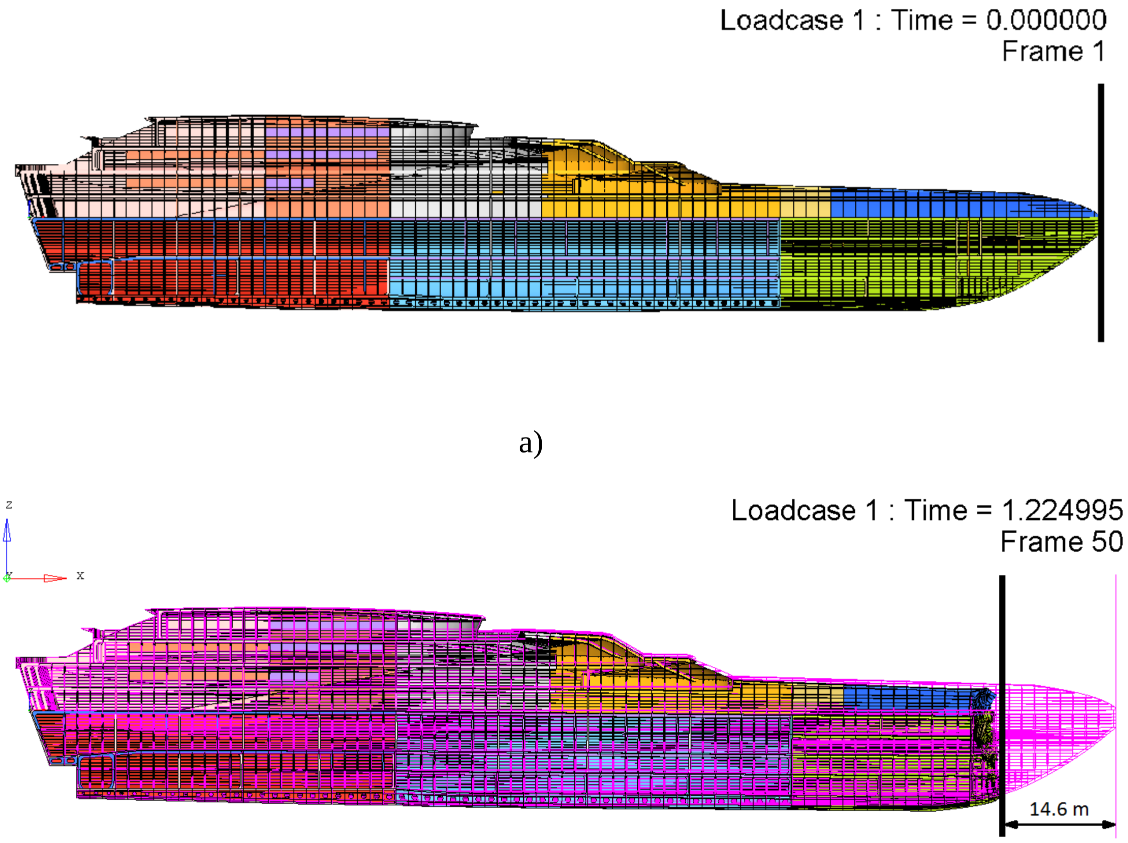
A full Finite Element computer model of the CLF boat was used in order to accurately capture the stress wave propagation through the structure. Correct load distribution and propagation has significant influence in crash analysis as it enables for accurate modelling of structure collapse. Even though the crush of the structure is most likely to be localised to the front of the boat, the propagating stress wave may induce stresses exceeding the material strength at different vulnerable areas resulting in the collapse of the structure away from the impact location.

In order to perform the analysis the following assumptions were made:

- The load case investigated normal impact against a rigid wall which represented a harbour peer.
- The motion of the catamaran was unrestrained in all degrees of freedom of translation and rotation as would be the case in a fluid with minimal shear properties.
- The velocity was set to 38 knots (20 m/s)
- The interface boat to water was ignored
- Simple elastic plastic material model was chosen to represent the material of the structure (MAT_PLASTIC_KINEMATIC). This material model was selected based on the fact that aluminium is isotropic and that it is well represented by a bilinear stress strain curve. It is a cost effective material model because of its simplified plastic response and is adapted to illustrate the design methodology. A failure strain of 30% was set to accommodate any structural damage using the failure plastic strain criterion for elements erosion (FS) switch in the material card. The material properties of used aluminium are shown in Table 3.

Table 3 Material properties of the standard medium grade aluminium

| | **Material model** | **Density (t/mm$^3$)** | **Young's Modulus (MPa)** |
|---|---|---|---|
| **Aluminum (deformable) – structural material** | 3 | 2.8e-9 | 70000 |
| **Aluminum (rigid) – for boat boundary condition** | 20 | 2.8e-9 | 70000 |



a)

b)

Figure 2 Deformation of the CLF bow: a) t=0, b) t=1.2s.

The results of the CLF impact analysis on the harbour structure showed considerable plastic deformation of the bow (see Figure 2). The structural collapse deformed the bow 11% of total vessel length within the crash bulkhead. Containment of deformation and rupture within this area ensured the hydrostatic integrity of the vessel after impact which ensures enough time for evacuation of CLF passengers. The deformation of the hull was restricted to the bow section which shows the potential in employment of the crumple zone to reduce the decelerations acting on the CLF occupants in case of the frontal impact.

The crash analysis revealed great danger to the boat occupants as the peak deceleration recorded was approximately 8g [20], which corresponds to the acceleration acting on the car occupants during crash. Very high deceleration and the fact that occupants are unrestrained result in a very high probability of the serious injury. The loads acting on the unrestrained passengers of the CLF are comparable to the loads sustained by unbelted car occupants. Statistics have shown that 49% of car crash fatalities in 2013 were unrestrained [21]. As passengers in the CLF vessel are travelling at the velocity of 40 knots (20 m/s), which is higher than the speed for unbelted occupant in occupant crash protection test [22], it is inevitable that the occupants would suffer from serious injuries after impact.

## 3. Model development

### *3.1 Derivation of the acceleration pulse*

In this investigation, the cabin of the CLF was assessed for occupant safety. It was based on injury criteria used extensively in automotive industry and achieved by the evaluation of injuries suffered by the occupant. The HYBRID III dummy model supplied by LSTC was used for assessment of CLF occupant injuries probability. Furthermore, the most injurious case was investigated with Total Human Model for Safety (THUMS) in order to evaluate the injuries sustained by the human organs.

The preliminary assessment of the CLF crash [20] enabled for the extraction of the acceleration pulse necessary for the investigation of the occupant safety. However, due to the high oscillations of the acceleration pulse extracted from the accelerometers it was decided to derive the acceleration based on the change of velocity of the CLF during the crash phase. For that purpose the node on the rear end of the trimaran was chosen and its velocity time history was extracted. The equation of the velocity curve is described with equation (1) and it was determined using a polynomial curve fitting procedure [19].

$$\begin{gathered} v(t) = 618.75t^6 - 4469.2t^5 + 8614.9t^4 + \\ 4495.4t^3 - 22689t^2 - 1102\mathrm{t} + 19560 \end{gathered} \tag{1}$$

Equation (1) was differentiated once in order to obtain the acceleration pulse. Therefore, the acceleration exerted on the vessel is given by equation (2) [19]:

$$\begin{gathered} a(t) = 3712.5t^5 - 22346t^4 + \\ 34459.6t^3 + 13486.2t^2 - 45378\mathrm{t} - 1102 \end{gathered} \tag{2}$$

For modelling purpose, the cabin has been model as static, while the reverse deceleration pulse was applied to the occupant.

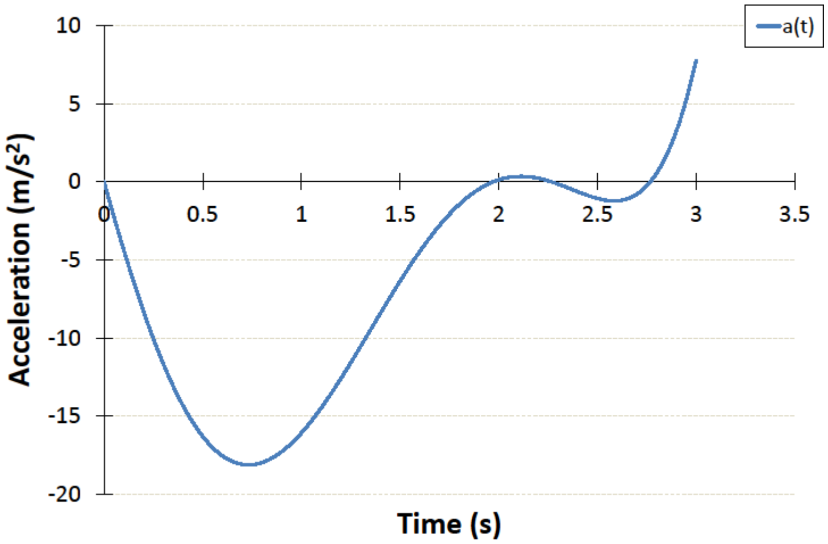


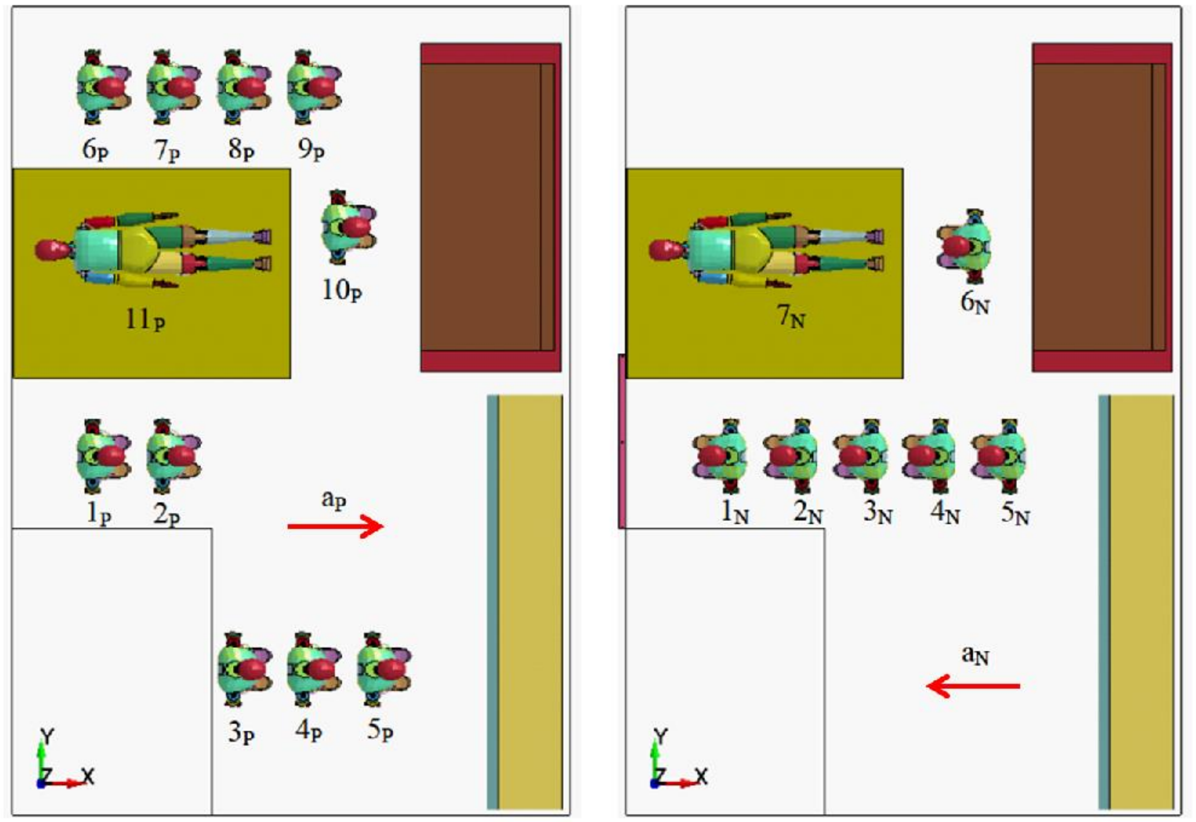
Figure 3 Acceleration pulse assigned to the occupant.

The derived acceleration pulse, shown in Figure 3, was assigned to the occupant of the trimaran cabin using LOAD_BODY_X control card in LS-DYNA [18].

### *3.2 Positioning and modelling approach*

Since the orientation of the cabin was not specified by the designer it was decided to investigate two different cabin orientations [19]. This was achieved by reversing of the occupant orientation as well as the crash deceleration field, as depicted in Figure 4. The arrow points the direction of the acceleration pulse and therefore the motion of the occupant. Moreover, Figure 4 a) and b) show the initial positions of the occupant within the cabin for positive and negative acceleration pulse respectively. Despite the initial position of the occupant, Figure 4 shows the orientation of the furniture within the cabin. Furniture within the cabin influence the behaviour of the occupant during the crash as well as the level of injuries suffered. It is closely related to the different structure impacted by the occupant. Therefore, furniture were modelled to the reasonable extent of details to provide as real as possible response of the structures.

The wardrobe was modelled using shell elements with 4 integration points across the thickness. This enable for the correct representation of bending stresses across the element, and consequently the accurate bending response of the structure. No material data of the wardrobe doors was available therefore it was assumed that they were made of 1 cm thick MDF panels. The material properties of the doors are given in Table 4.



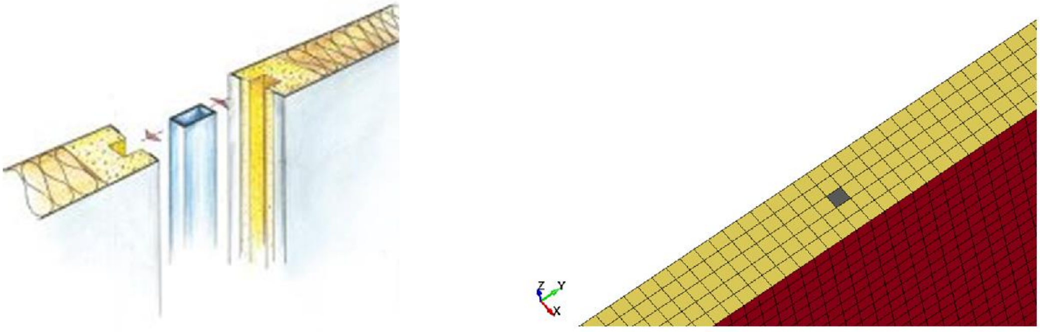
a) b)

Figure 4 Dummy positions a) positive acceleration pulse, b) negative acceleration pulse.

The bed and sofa were modelled with constant stress solid elements. Stiffness hourglass control with exact volume integration was used to improve the accuracy of the solid elements used in the analyses. Constant stress solid elements were used as the study is not focused in analysing the stress levels in the furniture (and their subsequent damage), but defining the right contact stiffness between the furniture and the occupant in order to generate an injury. The top of the bed and sitting area of the sofa were modelled with low density foam material model (see Table 4) in order to imitate the soft cushions of the furniture. However, in the analyses, where no contact between the occupant and the bed or sofa was expected, the foam material was exchanged with material rigid to reduce the computational time. For the cases where the occupant was laying on the bed or hitting the sofa, friction was defined as part of the contact parameters. This enabled for more realistic interaction of the dummy with furniture.

Table 4 Material properties of selected materials

| Component | Material model | Density $(t/mm^3)$ | Young's Modulus (MPa) | Poisson's ratio (-) | Yield stress (MPa) |
|---|---|---|---|---|---|
| **Bed mattress** | 57 | 3.5e-11 | 50 | N/A | N/A |
| **Bed base** | 20 | 2.8e-9 | 70000 | 0.3 | N/A |
| **Sofa soft** | 57 | 3.5e-11 | 50 | N/A | N/A |
| **Sofa base** | 20 | 2.8e-9 | 70000 | 0.3 | N/A |
| **Wardrobe door (MDF)** | 3 | 7.5e-10 | 4000 | 0.11 | 10 |



a)

b)

Figure 5 a) Cross section and design of the wall panel, b) FE model of the impacted wall.

Each of the walls was made of 50 mm thick steel/rock wool sandwich panels. The actual design of the wall is shown in Figure 5. Due to the lack of material properties for the wool the core of the wall was modelled with low density foam material model assigned to 5 layers of solid elements. This enabled to represent the cushioning effect of the rock wool sufficiently well. The walls steel face sheets were modelled using shell elements with four integration points through the thickness and material elastic plastic. The wall panels were mounted to the lower and upper deck using steel stiffeners which were also used as connectors between the wall panels (see Figure 5 a)). The width of each wall panel was 600 mm, defining the spacing between the steel stiffeners. In order to simplify the modelling of the wall each stiffener was represented with a layer of solid elements embedded within the foam as shown in Figure 5b). It needs to be highlighted that the real construction of the walls was only modelled where applicable. Namely, in the analyses where the acceleration pulse was negative, as these were the only cases where passenger was expected to hit the wall. Otherwise, the walls were modelled using shell elements and material rigid. The limitation of the detailed wall design was performed in order to reduce the computation cost of the analysis. Any holes and cavities within the wall panels were neglected as they would have a marginal influence on the analyses results as well as they would introduce undesirable complexity into the model.

The floor of the cabin was modelled as a rigid wall. In order to model the correct interaction between the floor and the passenger friction was introduced into the interface between the occupant and the rigid wall. Finally, the gravity loading was applied to the dummy.

## 3. Injury probability assessment with Hybrid III dummy model

The HYBRID III standing dummy model used for this research represents the 50th Percentile Male Crash Test Dummy used worldwide in the automotive crash tests [23]. This model was chosen as it is the most generic crash test dummy, containing calibrated means to record injury criteria in the frontal direction [24]. The model was developed by LSTC as a standing dummy for the frontal crash applications, and therefore the analyses shown in this section are only limited to the frontal impact scenarios.

Eighteen different dummy positions were considered in this study. The investigated scenarios consisted of eleven impacts with the positive acceleration pulse and seven with the negative acceleration pulse. Presented scenarios notations correspond to the initial dummy location (see Figure 4 a) and b)) denoted with a number and the acceleration direction – 'P' and 'N' for Positive and Negative acceleration pulse respectively [19]. The impacted structure was dependent on the direction of the acceleration pulse. In all impact scenarios with positive pulse the dummy impact on the wardrobe or sofa, while for the negative pulse the dummy hit the walls. Based on the injury assessment, it is possible to suggest the best orientation of the cabin, in terms of the occupant safety.

The injury criteria used in the evaluation of the boat occupant safety are the most commonly used criteria for the assessment of the car design and safety, which relate to the head, neck and chest. HIC is a design criterion for head impacts, which is based on the accelerations acting on head within a specified timeframe. According to NHTSA [16], HIC criterion is evaluated for all dummy sizes over a maximum time interval of 15 milliseconds with a limit of 700 for 50th percentile male. The HIC criterion is given with the equation (3):

$$HIC = max\left[\frac{1}{t_2-t_1}\int_{t1}^{t2} a(t)dt\right]^{2.5}(t_2-t_1) \qquad (3)$$

Neck Injury Criterion (NIJ) is an injury criterion used in automotive design for prediction of neck tolerance limits for compression, tension, shear, extension and flexion moments. The tolerance values were established among the test on cadavers and volunteers. A Nij value above 1.0 is considered to be injurious and above automotive safety legal requirements.

The last criterion used in evaluation of the occupant safety was a chest deflection which measures the compression of the chest cage near the solar plexus. It is considered that a chest compression above 65 mm is injurious.

The injury criteria described above were developed in order to relate the risk to human life or injury to the mechanical responses recorded by crash test dummies. It is achieved by relation of the injury criteria to the Abbreviated Injury Scale, which is the anatomically based injury severity scoring system. It classifies injuries for each body segment individually and relates its severity on a 6 point scale. AIS was developed for the Association for the Advancement of Automotive Medicine to provide standardised terminology for description of injuries severity. The injury criteria (HIC, NIJ and thorax injury) are linked to AIS through the Prasad-Mertz probability curves [16].

In order, to identify occupant injuries the following data were extracted from the joints and nodes of the dummy: head acceleration, chest deflection, impact forces and pitch moment at the neck. The results of the numerical analyses, presented in Table 5 enabled for the assessment of the Head Injury Criterion (HIC) and the Normalised Neck Injury Criterion (NIJ). Moreover, based on the injury criteria, the probabilities of the injuries were estimated using the Abbreviated Injury Scale (AIS) for different body regions. The probabilities of the corresponding injuries were assessed for the skull fracture (AIS >=2) for head and serious injuries (AIS>=3) for neck and chest, which is equivalent to the serious injury. However, considering that the injury probability was assessed for the head, neck and chest the serious injury can most likely lead to death of the occupant. Table 6 presents the probability of head, neck and chest injury.

Analysis 8P was chosen to illustrate the occupant impact and the methodology followed during the post processing of the results.

The trace of the dummy impact trajectory is shown in Figure 6. It was observed that initially the dummy hits the armrest and the sofa cushions. Then, as the impact progresses, it rotates about its centre of gravity and hits the sofa with his back. The rotation of the dummy is caused by the impact on the armrest.

The multiple impacts were confirmed on the head acceleration graph shown in Figure 7. The initial increase in head acceleration is caused by initial impact on the sofa armrest. This is followed by the head impact on the sofa cushion which occurred at time t=0.645 s. The head impact is pronounced by the considerable deceleration resulting in HIC value of 2067, which leads to 78% probability of the skull fracture. The third peak visible in the graph was after the dummy rotated and hit the backrest of the sofa. Afterwards shear (X force), tensile (Z force) forces and the bending moment at the occupant’s neck were extracted. Based on the time history of these values, the neck injury criterion was calculated. NIJ values enabled to estimate the probability of the neck injury using the AIS. Therefore, there is a 52% probability that the cabin occupant would suffer a serious neck injury in similar impact scenario.

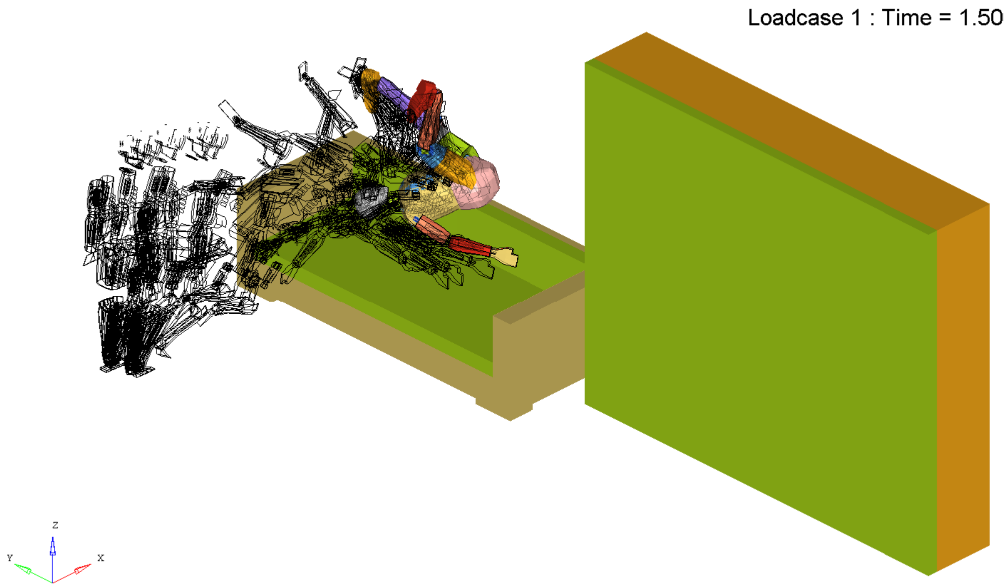


Figure 6 Dummy impact trajectory for 8P scenario.

Subsequently, the chest deflection was measured using the spring element implemented into the dummy thorax. Based on the maximum chest deflection and the Abbreviated Injury Scale curve for thorax the probability of the thorax injury was estimated at level of 11%.

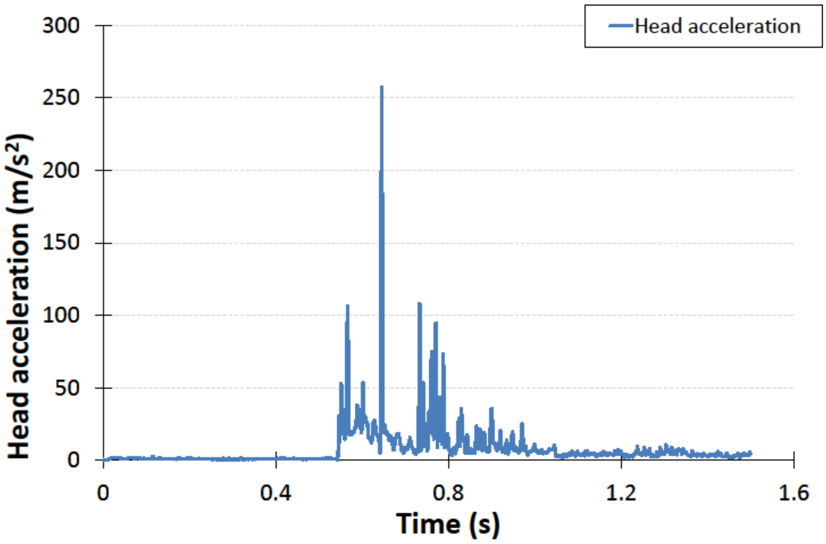


Figure 7 Head acceleration.

Results presented in Table 5 and Table 6 clearly show high dependence between the value of the injury criterion and the occupant distance from the obstacle. This finding is true for the cases where occupant was hitting the wall or wardrobe directly without other obstacles on its way. The further the occupant was, the higher the accelerations and forces acting on the dummy and therefore the higher probability of the injury. This was expected as the passenger was unrestrained.

Table 5 Injury Criteria

| Case | Distance to obstacle (mm) | Max. Head acceleration (g) | HIC | Max. Chest deflection (mm) | NIJ Tension | NIJ Compression | NIJ Flexion | NIJ Extension |
|---|---|---|---|---|---|---|---|---|
| **1P** | 2580 | 372.6 | 6999 | 35.1 | 7.76 | 3.73 | 0.08 | 6.81 |
| **2P** | 2080 | 457.3 | 7615 | 13.4 | 7.49 | 1.28 | 0.98 | 4.56 |
| **3P** | 1580 | 99.9 | 432 | 46.9 | 1.05 | 0.29 | 0.97 | 1.74 |
| **4P** | 1080 | 67.2 | 273 | 30.3 | 1.45 | 0.52 | 0.92 | 0.82 |
| **5P** | 580 | 50.8 | 88 | 27.1 | 0.62 | 0.32 | 0.54 | 0.61 |
| **6P** | 2110 (3170) | 368.1 | 10180 | 32.4 | 2.75 | 3.07 | 2.68 | 2.62 |
| **7P** | 1610 (2670) | 208.0 | 1039 | 63.2 | 1.29 | 0.81 | 0.88 | 0.66 |
| **8P** | 1110 (2170) | 258.4 | 2067 | 11.0 | 0.97 | 0.89 | 1.69 | 1.55 |
| **9P** | 610 (1670) | 357.0 | 6685 | 7.0 | 1.18 | 2.67 | 0.94 | 1.68 |
| **10P** | 360 (1420) | 376.5 | 4526 | 57.4 | 0.65 | 3.36 | 4.41 | 3.79 |
| **11P** | N/A | 136.3 | 466.3 | 10.8 | 0.73 | 0.92 | 0.50 | 2.44 |
| **1N** | 520 | 112.3 | 389 | 24.6 | 0.41 | 0.39 | 0.50 | 0.76 |
| **2N** | 1020 | 171.5 | 1173 | 35.4 | 0.76 | 0.48 | 0.81 | 1.59 |
| **3N** | 1520 | 199.5 | 2225 | 61.9 | 1.32 | 1.07 | 1.13 | 3.68 |
| **4N** | 2020 | 241.8 | 2916 | 32.1 | 1.58 | 1.47 | 1.51 | 6.35 |
| **5N** | 2520 | 219.1 | 3779 | 25.1 | 0.60 | 0.62 | 0.70 | 11.07 |
| **6N** | 280 (2280) | 157.1 | 1935 | 44 | 1.00 | 1.38 | 1.99 | 4.04 |
| **7N** | N/A | 57.6 | 142 | 4 | 0.26 | 0.23 | 0.91 | 0.32 |

Table 6 Probability of injury

| Case | Distance to obstacle (mm) | AIS 2+ head (probability) (%) | AIS 3+ Neck (probability ) (%) | AIS 3+ Chest (probability ) (%) |
|---|---|---|---|---|
| **1P** | 2580 | >90 | 100 | 27 |
| **2P** | 2080 | >90 | 100 | 13 |
| **3P** | 1580 | 13 | 55 | 40 |
| **4P** | 1080 | 4 | 33 | 23 |
| **5P** | 580 | 1 | 11 | 21 |
| **6P** | 2110 (3170) | >90 | 94 | 25 |
| **7P** | 1610 (2670) | 48 | 34 | 60 |
| **8P** | 1110 (2170) | 78 | 52 | 11 |
| **9P** | 610 (1670) | >90 | 87 | 9 |
| **10P** | 360 (1420) | >90 | 97 | 53 |
| **11P** | N/A | 17 | 82 | 11 |
| **1N** | 520 | 11 | 15 | 18 |
| **2N** | 1020 | 50 | 52 | 27 |
| **3N** | 1520 | 81 | 97 | 58 |
| **4N** | 2020 | 88 | 100 | 25 |
| **5N** | 2520 | >90 | 100 | 19 |
| **6N** | 280 (2280) | 76 | 99 | 37 |
| **7N** | N/A | 1 | 20 | 7 |

### *4.1 Evaluation of a passenger safe crash position with Hybrid III dummy*

Based on the high risk of the serious injuries involved in the case of the boat crash and its distance to obstacle dependency, it was decided to determine the safe position for the occupants which would reduce the high probability of occupant injury. The safe position could be advised to boat passengers when the occurrence of the crash is inevitable.

In order to determine a safe passenger position, it is recommended to choose part of the cabin with energy absorption properties as well as free of sharp edges. Therefore, the walls and wardrobe doors were considered to have the most prospect for a safe position. Considering that wardrobe doors could break during the crash and therefore cause additional safety hazard to the occupant, it was decided to perform the bracing position investigation using the wall structure. This decision was also supported by the fact that the detailed structure of the wall was available for the FE analysis, which was not the case for the wardrobe.

High dependency of the injuries criteria values on the distance from the obstacle led to a conclusion that the closer the occupant is from the obstacle the lower probability of the injury. Therefore, the dummy was placed as close to the wall as possible. Moreover, two different positions of the dummy were considered, namely, the frontal and posterior positions (see Figure 8).

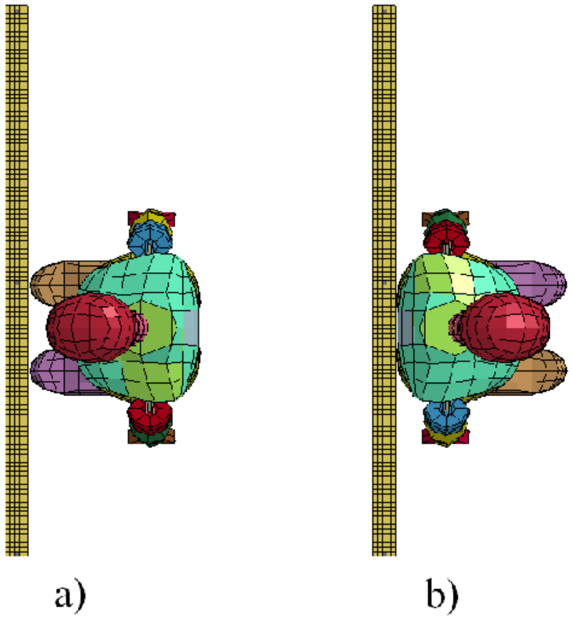


Figure 8 Proposed safe positions: a) frontal, b) posterior.

The injuries criteria and the probability of the injury for the safe position investigation are shown in Table 7 and Table 8 respectively. From these tables it can be seen that the values of the injury criteria are significantly reduced in both cases. Slightly higher HIC value for frontal dummy position was related to the fact that there was no contact between the head and the wall in the posterior impact scenario, which was related to the HYBRID III dummy limitation to the frontal impacts only. Therefore, it is recommended that further studies are conducted with more detailed model to decide which of the positions is safer for the occupants.

Table 7 Injury criteria for the safe position analysis

| Case | Head acceleration (max) (g) | HIC | Chest deflection (max) (mm) | NIJ Tension | NIJ Compression | NIJ Flexion | NIJ Extension |
|---|---|---|---|---|---|---|---|
| **0NF** | 17.4 | 5.9 | 10.3 | 0.12 | 0.08 | 0.11 | 0.13 |
| **0NP** | 2.5 | 0.14 | 0.8 | 0.01 | 0.00 | 0.05 | 0.04 |

Table 8 Probability of the injury for the safe position analysis

| Case | AIS 2+ head (probability ) (%) | AIS 3+ Neck (probability ) (%) | AIS 3+ Chest (probability ) (%) |
|---|---|---|---|
| **0NF** | 0 | 4 | 10 |
| **0NP** | 0 | 4 | 6 |

## 5. Injury prediction with THUMS

The initial safety analysis for the CLF occupants performed with Hybrid III dummy model showed very high risk of severe injuries which may result fatal. Therefore, it was decided to perform more detailed studies using Total Human Model for Safety (THUMS) to determine whether these findings are reflected in more advanced analysis. Application of more detailed model enabled to take into account the differences of the model orientation as it eliminated the restriction of the dummy model, which was calibrated only for frontal impact. The analyses with the dummy model identified close relation of the injury probability and the distance to the obstacle, therefore the analyses with the human model were performed for the THUMS located as far as possible from the impacted surface. Furthermore, both safety positions identified with the Hybrid III dummy were investigated to confirm the reliability and safety of the solution.

THUMS 4.0 used for these studies is a state of the art human model which includes a skeleton structure, internal organs and soft tissues which makes it a suitable candidate to analyse accident trauma. The THUMS model has been correlated at the limbs level [25] as well as successfully validated against rigid impactor tests, in frontal [25,26], lateral and oblique impact cases [27].

Due to accumulative nature of the injuries suffered by humans strains and pressures were plotted as the maximum (minimum) values accumulated along the impact event rather than transient values. The injuries were assessed for the skeleton and most important organs of the human body, i.e. brain, heart, liver, spleen and kidneys. Thresholds for the injuries for a certain body parts are shown in Table 9.

Table 9 Thresholds for the injuries in THUMS

| **Injury type** | **Type of load** | **Threshold** |
|---|---|---:|
| **Bone fracture** | Strain | 3% |
| **Brain contusion** | Pressure | +/- 230 kPa |
| **DAI** | Strain | >21% |
| **Heart tissue** | strain | 30% |
| **Liver and kidneys** | strain | 30% |

Figure 9 shows two impact cases for frontal T5NF (Figure 9a) and posterior T5NP (Figure 9b) orientations of the THUMS within the cabin. The impact cases with THUMS correspond to the scenario 5N. This impact case was chosen as it has one of the highest injury probabilities among all the performed analyses with Hybrid III dummy model. In that impact case the distance of the occupant and the impacted structure is the highest possible. This position was also chosen based on the finding from the initial cabin safety investigation, which states that the injury probability increases with the distance from the obstacle.

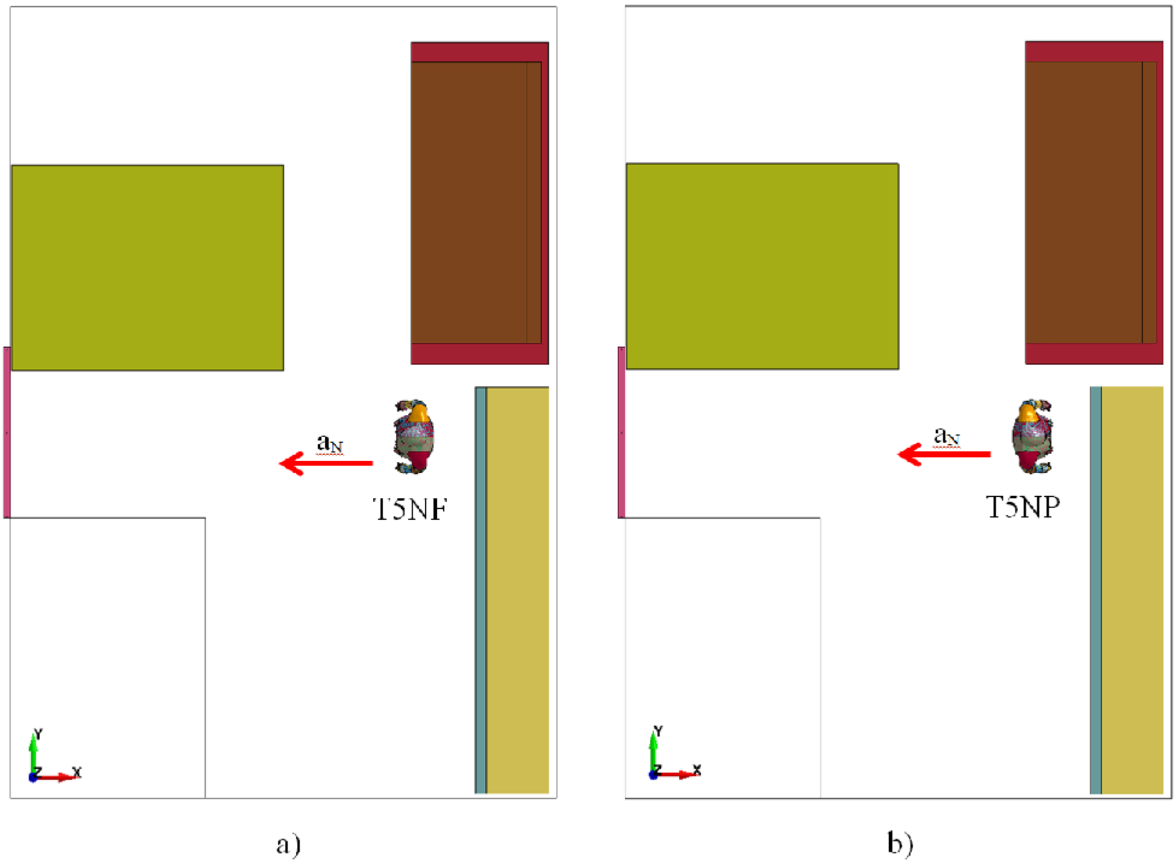


Figure 9 Cabin orientations for analysis with THUMS model (Position 5N).

Skeleton was the first body structure taken into consideration in the injury assessment performed with THUMS model. The maximum plastic strains of the frontal and posterior bone structure for the THUMS in T5NF impact case are shown in Figure 10. Only top part of the bone structure (above pelvis) was shown for better visualisation of the results. This was possible due to the lack of fracture in lower extremities. From Figure 10a it can be seen that there is a high concentration of plastic strains along the spine in the thoracic vertebras. High strains are also spread from the top part of the thoracic region to the cervical spine (see Figure 10b). According to Burstein et al. [28] and McCalden et al. [29] threshold for bone fracture is 3% of plastic strain, therefore it is very likely that the boat occupant standing in the position T5NF would suffer from an extensive fracture of vertebras after collision with the cabin wall. Very high concentration of the plastic strains exceeding the fracture limit would results in the damage of vertebras and very likely injury of the spinal cord. In addition to the spine region the excessive plastic strains were found in the skull, collarbone and sternum. This suggests that corresponding bones would fracture cause life changing injuries.

Both spine and head injuries were identified during the analysis with a Hybrid III dummy, which confirms that this impact scenario would result in the serious injuries of the occupant standing in position 5N.

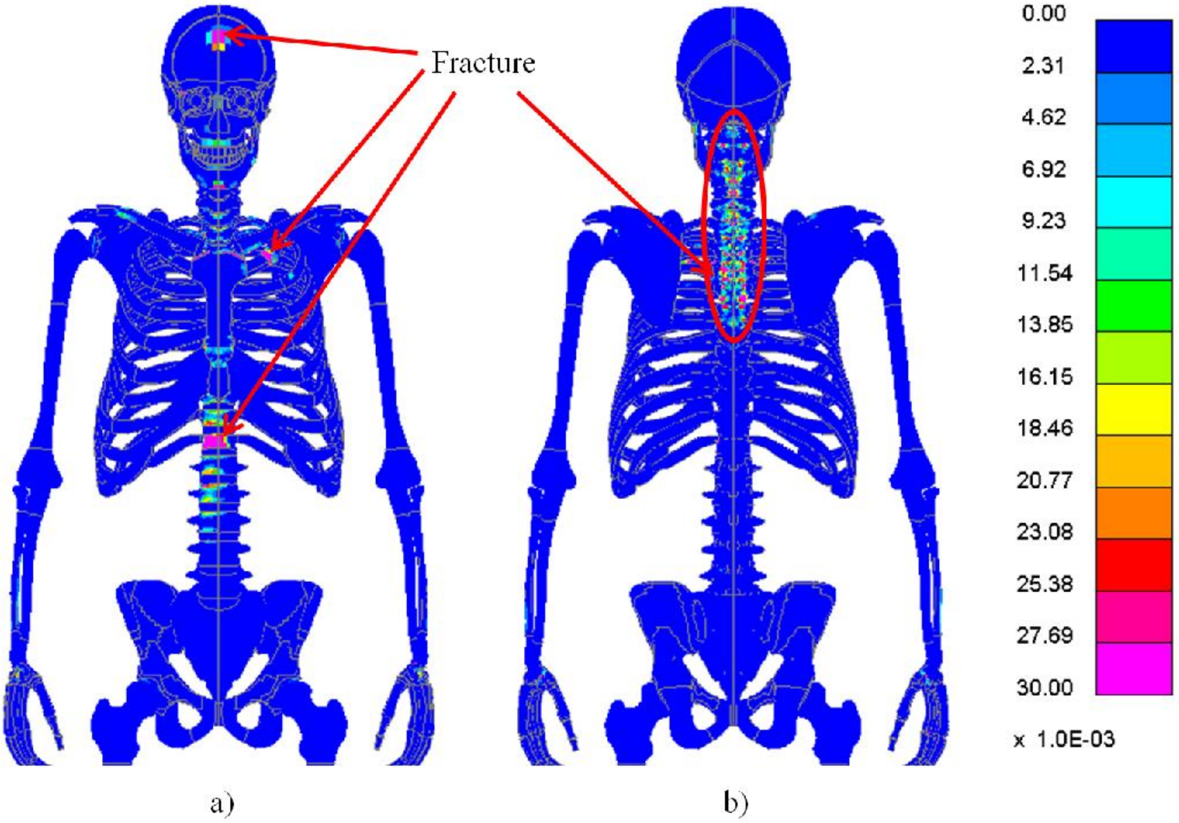
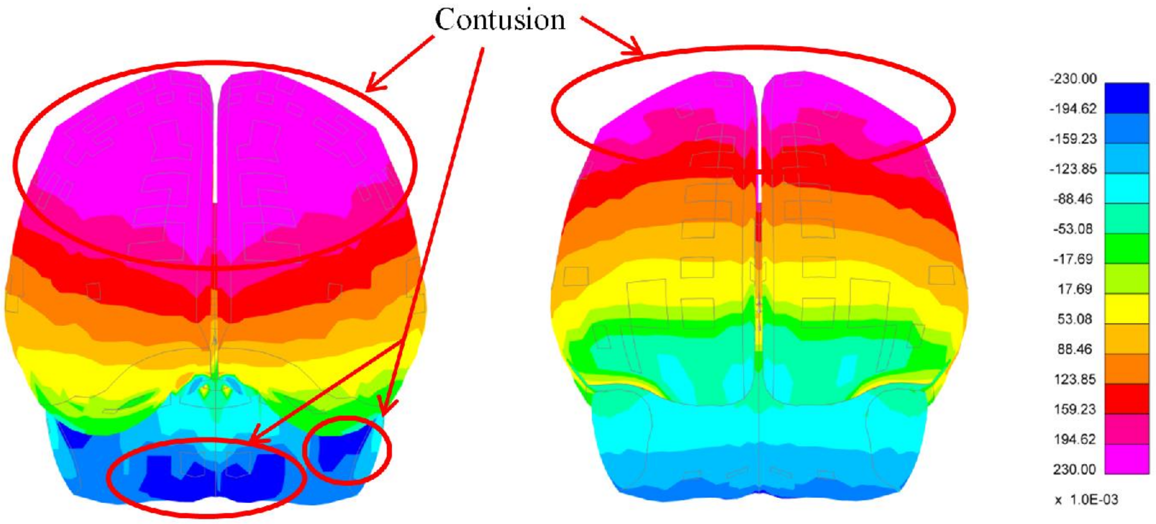


Figure 10 Maximum plastic strains (-) in skeleton structure of THUMS after frontal impact: a) front view, b) back view.

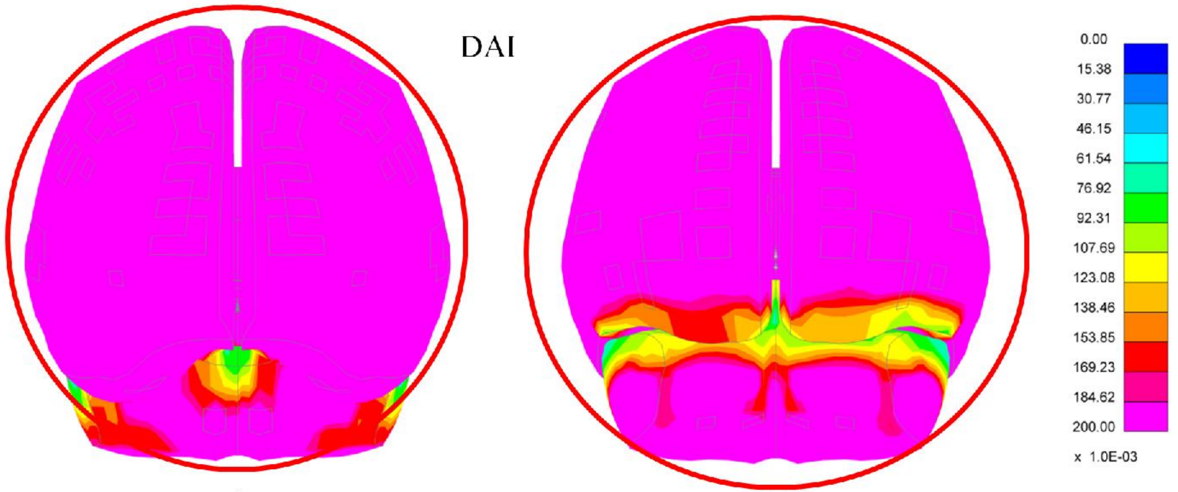
The next stage of the THUMS injury assessment was performed for the soft organs, starting from the brain. The brain contusion is caused by the translational acceleration and the diffuse axon injury (DAI) results from excessive angular acceleration of the brain [25]. THUMS enables for assessment of both injury types based on different approaches. The brain contusion can be assessed with the pressure criterion proposed by Ward et al. [30] which states the injury threshold for ±230 kPa. Similarly, the DAI can be assessed with the injury criterion based on the maximum principle strain in the brain. The threshold for DAI was specified by Bain and Meaney [31] as strain greater than 21% for white matter and by Takhounts et al. [32] as a strain range between 15% and 25%. Based on the above research it was decided to set up the DAI threshold as 20% of maximum principal strain.

Figure 11 shows pressure distribution in the brain. From this figure it can be seen that the area of threshold pressure is localised in the top part of the cortex in frontal and parietal lobe. Very low pressure region was found in the bottom part of the cerebrum (see Figure 11a). The locations with pressure higher (lower) or equal to 230 kPa (-230 kPa) would most likely suffer from brain contusion. In spite of the brain contusion the occupant would suffer very extensive DAI. Figure 12 shows that the principal strain in majority of the brain is higher than the DAI threshold value.



a) b)

Figure 11 Pressure distribution (MPa) for brain contusion after frontal impact: a) front view, b) back view.

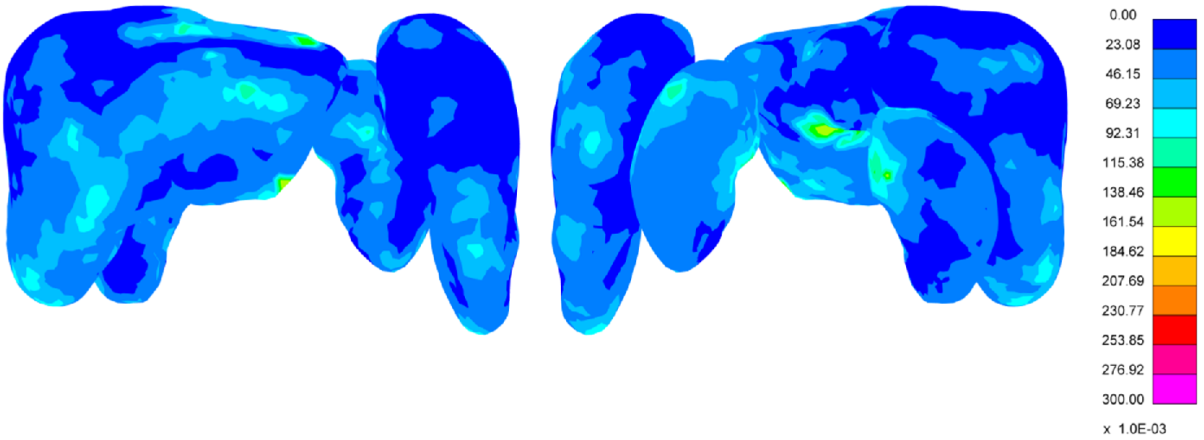


a) b)

Figure 12 Maximum principal strains distribution (-) for diffuse axon injury (DAI) after frontal impact: a) front view, b) back view.

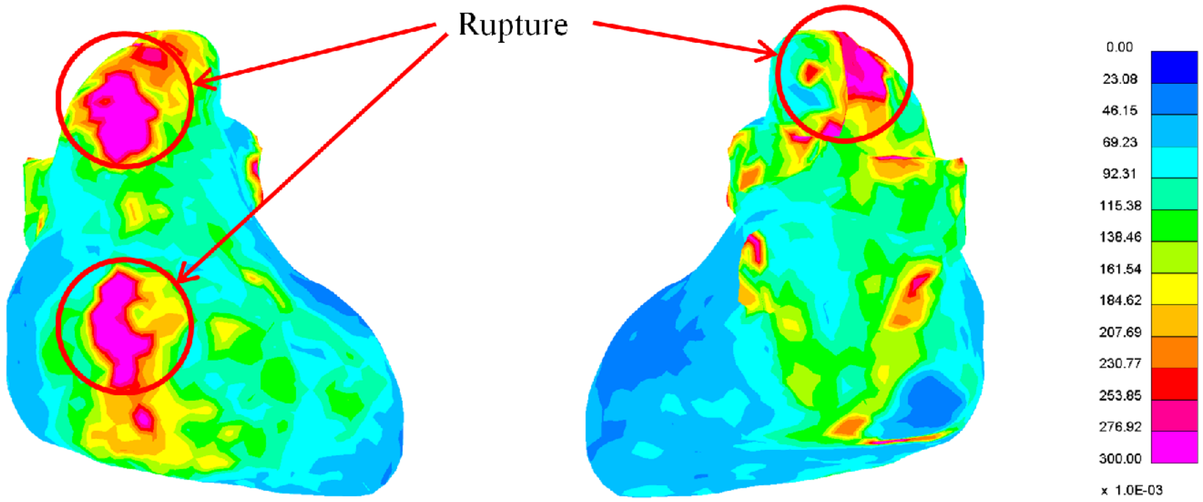
The results of the analysis for internal organs enclosed in the chest, namely: heart, spleen, liver and kidneys are shown in Figure 13 and Figure 14. Both figures show plastic strain distribution on the exterior surface of the organs. Based on the studies of Yamada [33] the threshold strain for the heart tissue was set us 30% of strain. Similarly the threshold for the remaining organs was set to 30% according to Melvin et al. [34] and Toyota Motors [25].

From Figure 13 it can be seen that heart would suffer from extensive bruises rupture. High concentration of strains above threshold is visible in the right ventricle and right atrium, as well as in the neighbourhood of left atrium and pulmonary artery. The maximum plastic strain recorded in the heart was 100%, which if significantly higher than the limit for tissue rupture. Figure 14 shows that none of the considered internal organs (different than heart) suffered from excessive strains. The maximum strain of 15% was localised in the liver.



a) b)

Figure 13 Plastic strains distribution in the heart - rupture of heart tissue after frontal impact: a) front view, b) back view.



a) b)

Figure 14 Plastic strains distribution in thoracic organs (spleen, liver and kidneys) - rupture of organs tissue after frontal impact: a) front view, b) back view.

The same analysis was performed with THUMS model and posterior position to the impact direction. Based on the injury criteria specified in the description of frontal impact boat occupant would suffer from spine injury in the thoracic and neck regions. Moreover, extensive ribs fracture was most likely resulting in separation of ribs from sternum and lungs perforation was identified within the model. Except bones fracture the occupant suffered from brain contusion localised in occipital lobe and cerebrum, as well as, extensive DAI. Plastic strain distribution for the organs enclosed in the rib cage indicates extensive rupture of the liver and heart particularly right ventricle, left ventricle and pulmonary artery. No indication of excessive strains was found in spleen or kidneys.

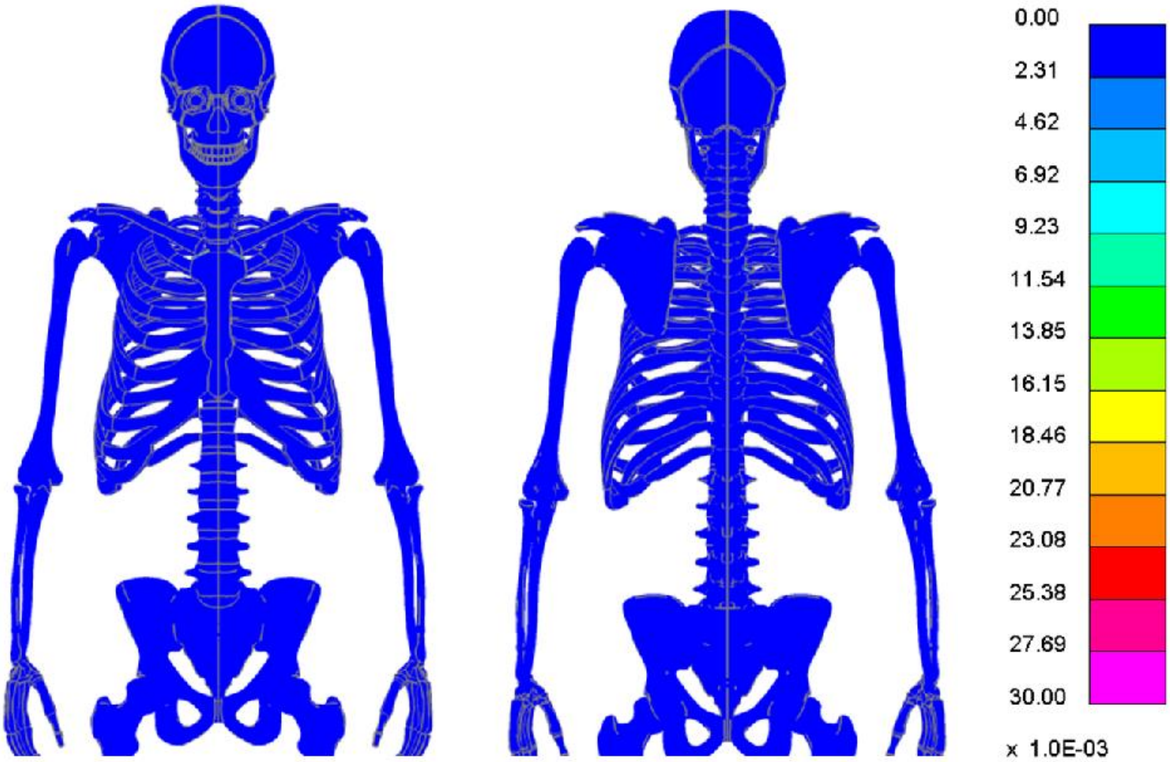
Both analyses with THUMS model showed very severe injuries suffered by the CLF cabin occupant. Results of these analyses are in close agreement with the analyses performed with the Hybrid III dummy model, where very high probability of the severe injuries was found for head and neck. On the other hand the results for chest are in contradiction between the Hybrid III and THUMS analyses. The results obtained with a dummy model do not show any risk for the chest while the analyses with detailed human model allowed for identification of injury within the heart and chest cage bones. The discrepancy between the analyses is related to the simplification of the HYBRID III model as it predicts the injuries of the chest based on the chest deflection only and it does not take into account acceleration of the internal organs. Furthermore, the spine of the HYBRID III is flexible only in the neck region in comparison to the whole length of the spine of THUMS model. Spine flexibility influences the kinematics of the model after impact which results in differences in the thorax response and therefore different level of injuries.

### *5.1 Evaluation of a passenger safe crash position with THUMS model*

The last stage of the injury prediction analysis was the investigation on the safety position. The initial studies performed with HYBRID III dummy model shown significant reduction of injuries probabilities for the boat occupant taking bracing position. However, since the HYBRID III is only a simplified model it does not allow for prediction of injuries of particular organs and the THUMS model was used to confirm that the safe position is credible.

Both frontal and posterior safety positions were investigated for the injury reduction. The thorough analysis of the simulations results was performed following the same methodology as in the case of T5N impact analyses.

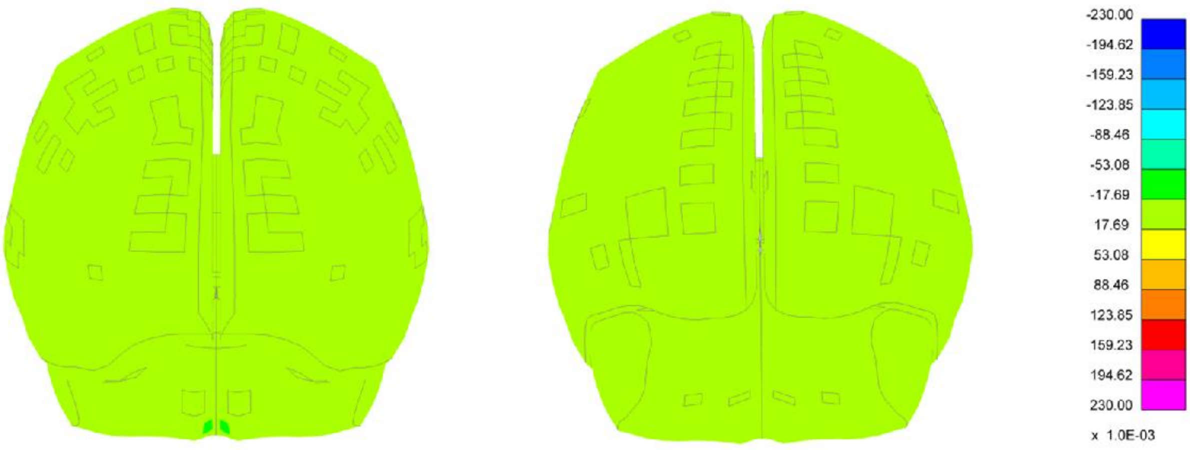
Figure 15 shows the maximum plastic strain for the skeleton structure of the boat occupant. It could be seen that there is no concentration of high plastic strains within the bones structure. In contrary to T5NF analysis the skull, vertebras and ribs do not have any indication of excessive plastic strains which confirms that the occupant taking safety position would not suffer from any bone fracture.



a) b)

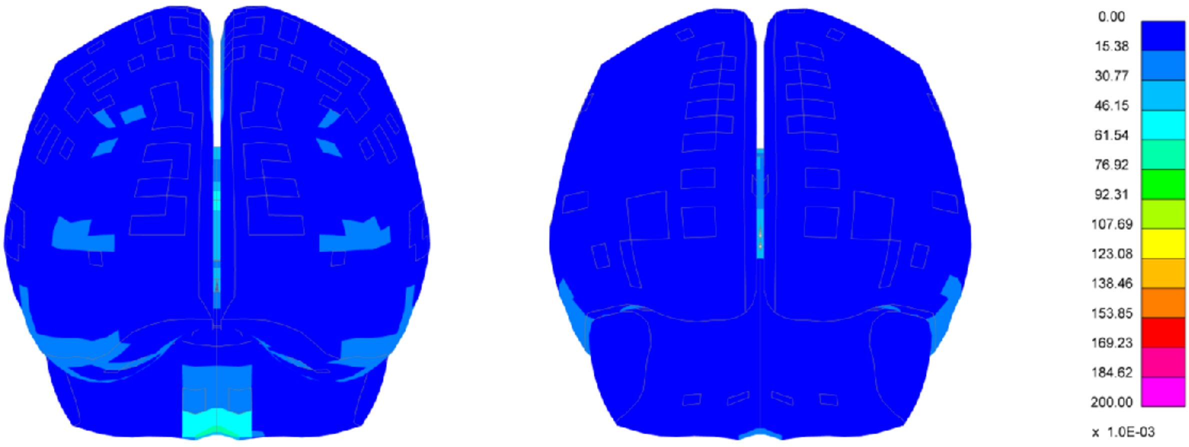
Figure 15 Maximum plastic strains (-) in skeleton structure of THUMS after impact for frontal safe position: a) front view, b) back view.

Figure 16 and Figure 17 show pressure distribution and maximum principal strain in white and grey matter respectively. Both figures indicate that the boat cabin occupant taking safety position during collision with the harbour structure would not suffer from the brain contusion or DAI. The maximum absolute pressure recorded during the impact was 10.2 kPa and the maximum principal strain was 6.1%.



a) b)

Figure 16 Pressure distribution (MPa) for brain contusion in frontal safe position: a) front view, b) back view.



a) b)

Figure 17 Maximum principal strains distribution for diffuse axon injury in frontal safe position: a) front view, b) back view.

Plastic strains distribution in the chest organs is shown in Figure 18 and Figure 19. Fringe levels distribution for these organs suggests that there is no plastic strain within these organs therefore none of the considered organs would suffer from rupture. In all organs the plastic strains remained on the zero level.

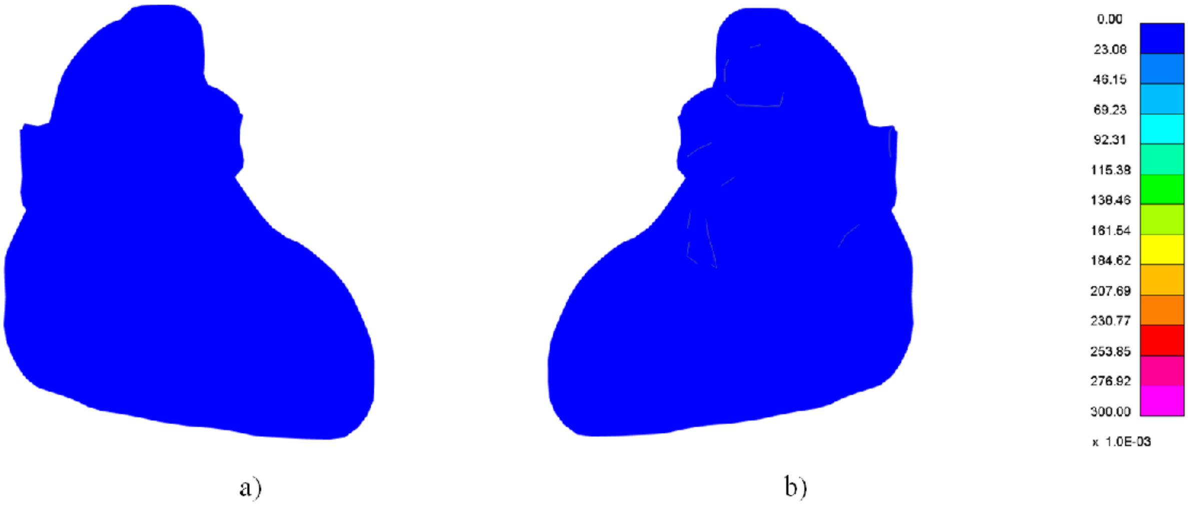


Figure 18 Plastic strains distribution in the heart - rupture of heart tissue in frontal safe position: a) front view, b) back view.

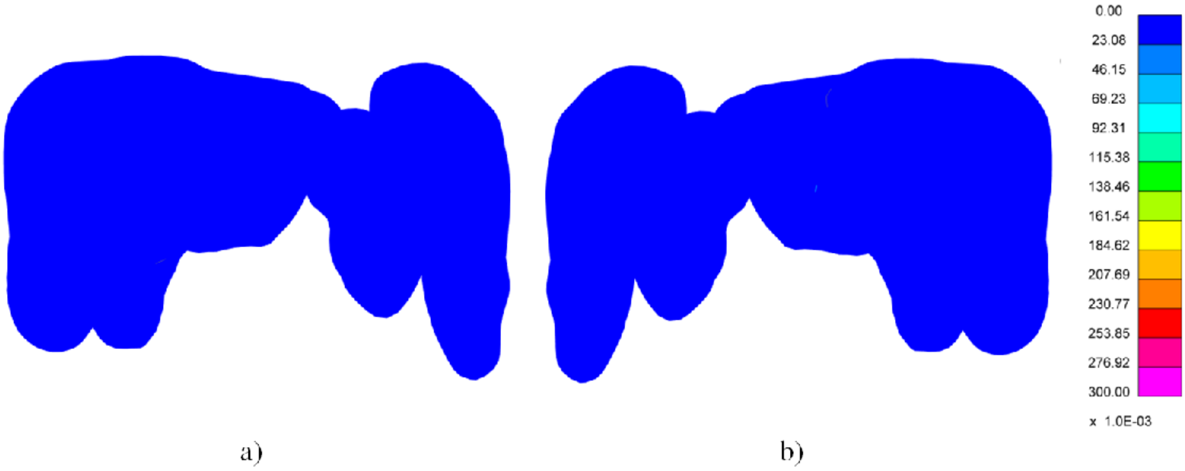
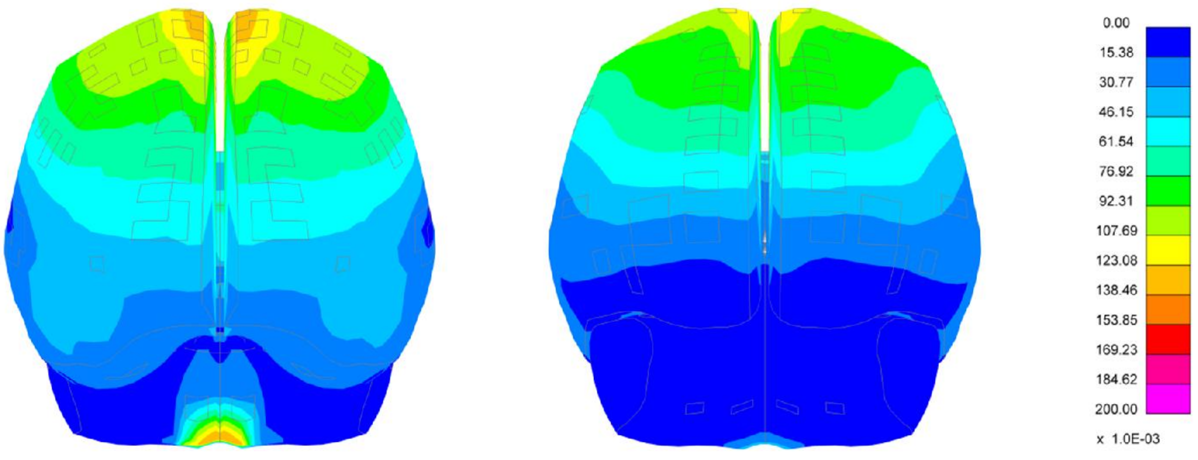


Figure 19 Plastic strains distribution in thoracic organs (spleen, liver and kidneys) - rupture of organs tissue in frontal safe position: a) front view, b) back view.

The analysis of the safety position for the THUMS standing backwards showed very similar results as the analysis of frontal bracing position. The skeletal structure did not show any indication of excessive plastic strains which could lead to the fracture of the bones. Plastic strains for the chest organs, namely heart, liver, spleen and stomach stayed on the zero level, therefore no rupture of these organs is expected. The pressure level within the brain oscillates close to 0kPa therefore the occupant would not suffer from the brain contusion. The only difference between the frontal and posterior safety position was noticed within the maximum principal strain distribution. Maximum principal strain was recorded as a 15.4% (see Figure 20). That high strain distribution is within the limit considered within these studies (20%), however, according to Takhounts et al. [32] that level of strain may still lead to the beginning of DAI.

The analyses of the safety positions performed with the THUMS model show good level of agreement with the initial studies performed with the HYBRID III dummy model. Both studies shown significant reduction of the injury risk to the occupant and therefore could be suggested to the boat occupants in case of inevitable frontal crash of the CLF. However, the latest results show that the frontal position is preferred due to the likelihood of DAI in case of posterior safety position.



a) b)

Figure 20 Maximum principal strain distribution for diffuse axon injury (DAI) in posterior safe position: a) front view, b) back view.

## 6. DISCUSSION

The studies presented in this paper investigate the probability and severity of the injuries suffered by the trimaran boat occupant during the crash with a harbour structure. The FEA cabin model prepared for the purpose of the analyses was built to represent as best as possible the structure of the boat cabin. Furniture and the walls were modelled with good accuracy in the areas which were impacted by the occupant.

The HYBRID III dummy model was used for the initial evaluation of the injury criteria and trauma probability for a different occupant location within the cabin. Eighteen occupant positions were investigated within this study, standing and unrestrained.

The 50th percentile Hybrid III dummy model is a finite element representation of the most commonly used dummy in automotive industry. The responses of FE sitting model were validated against the impact tests conducted on HYBRID III dummy for head, thorax and neck. The detailed description and the results of the validation were described in [35], [36] and [37]. The standing dummy is using the full injury calibration of the sitting dummy. The standing position of the dummy is obtained through the implementation of the different pelvis. According to LSTC there are no official tests carried for the standing dummies (all tests are conducted on sitting or lying cadavers). However, the construction of the model is the same as the seated 50th percentile dummy; hence its injury outputs are validated. Moreover, the paper has shown that the injury outcomes of this Hybrid III model relate well to THUMS (calibrated human model), hence the standing Hybrid III injury criteria predictions are believable.

The results of the initial investigation showed that in most of the cases the trimaran boat occupant is subjected to very high risk of a serious injury in case of the CLF impacting a rigid object, like the harbour peer. In fourteen cases the probability of the serious injury was higher than 50% from which ten cases had a probability of serious injury higher than 80%.

The trauma sustained to the head, the neck and the chest would most likely result in life changing injuries of the boat occupants. Therefore it was decided to perform more comprehensive studies with very detailed human model which allows for determination of the injury location within the human body. Total Human Model for Safety developed by Toyota Motors [25] was used for this studies and the most injurious case, identified with the HYBRID III dummy, was chosen to be examined.

The investigation performed with the THUMS model confirmed the findings from initial investigation. Both, frontal and posterior T5N impacts result in very extensive injuries to the skeletal structure, brain and the heart of the cabin boat occupant. Studies with human model showed small discrepancies to the initial studies, explicitly, in terms of the heart injury. THUMS showed significant rupture of the heart tissue while the corresponding analysis with HYBRID III model did not indicate high injury probability to the chest of the occupant. These differences are related to the simplicity of the dummy model which considers only chest deflection and does not take into account acceleration and inertia of the organs in the chest injury criterion. Head and neck injury probabilities were predicted correctly with HYBRID III dummy model and they were confirmed with further analysis with THUMS, where both skull and brain injuries were identified. Based on these findings it is correct to assume that the most dangerous impact case was studied with the THUMS.

Thorough analysis of the initial investigation results showed dependency between the occupant distance from the obstacle and the injury criteria value. This observation enabled to determine the safe bracing position for the occupant when the crash is inevitable and is predicted in advance.

The initial investigation on the safety position showed that the risk of the occupant injury can be reduced when the occupant stands very close to the wall - closest to the impact direction. The reduction of the injuries probability is related to the fact the occupant throw projection speed was least and that the walls are made of sandwich panels which enable partial absorption of the impact energy by deflection of the steel face sheets and collapse of the core. This results in the lower acceleration and lower impact forces acting on the occupant’s body, and therefore lower probability of serious injury.

Initial investigation on the safe position was followed by the study with detailed human model. These studies confirmed that safe position significantly reduces the injuries suffered by the occupant. In both cases – frontal and posterior position, the THUMS model did not have any indication of the injuries to the skeletal structure and chest internal organs. In the case of frontal safe position brain was free of any excessive pressure or strains therefore it would not suffer from brain contusion nor DAI. However, in case of the posterior bracing position it is very likely that the occupant would suffer from DAI as the strains within the head exceeded 15% which is very close to the DAI threshold strain.

Significant reduction of the injury probability for the occupant taking a safety position was identified for a certain orientation of the cabin. Therefore, based on the results of this study, it is recommended that cabin GA (graphical arrangement) design should include clear wall space for passengers to brace in case of vessel collision and all the cabins should be oriented in the direction shown in Figure 4 b). In addition, all the furniture should be securely fastened to the vessel.

Injury prediction of the CLF vessel occupants shows successful application of the automotive technology in the marine. This opens possibilities for the transfer of more advanced technologies from automotive to marine design, especially in terms of occupant protection.

## 7. CONCLUSIONS

The injury assessment of the CLF occupant in case of a crash with the harbour peer was described in this paper. The impact case studied is the worst case scenario where the high speed vessel crashes at maximum speed into the rigid structure of the peer. The numerical investigation was performed using a nonlinear transient explicit Finite Element solver and consisted of two impact studies – an initial investigation performed with automotive dummy model and a comprehensive investigation utilising a detailed human model. The initial investigation consisted of 18 impact cases and enabled for identification of injuries probabilities for head, spine and thorax. The most severe impact case was further studied with a detailed human model.

Initial investigation, based on a HYBRID III crash test dummy, -revealed a very high risk of severe injuries to boat occupants, which was highly dependent on the distance of the passenger to the impacted obstacle (wall, sofa, wardrobe, etc.). The detailed analysis, using the human model, confirmed the findings of the initial investigation in terms of severe brain, chest and skeletal injuries to the vessel occupant. The human model, allowed the identification of detail location and specification of the injury including internal organs i.e. heart rupture and brain injuries.

Based on the dependency between the injury probability and the distance to the obstacle it was possible to determine the safe position of the cabin occupant during a vessel crash. Two safe positions were studied with both HYBRID III and THUMS models and confirmed a significant reduction in injury probability and its severity. According to the analyses with detailed human model, the frontal bracing safety position enables for complete elimination of injuries to the vital organs and bone structure, while the. Posterior position revealed substantial risk of diffuse axon injury.

Studies presented in this paper introduced the design methodology for occupant protection in the cabin design of high speed vessel. In this methodology the 50th percentile HYBRID III standing crash test dummy model is used to evaluate the probabilities of severe injuries sustained in the event of boat crash on the sea and to identify the most severe impact case. Further, the THUMS model is used for a detailed investigation of the trauma location and injuries level for the chosen impact cases. The final step of this methodology is the implementation of the most relevant safety procedure to reduce the injuries sustained by the vessel occupants.

It is envisaged that this design methodology could be used to improve the insensitivity of the HSC code to individual passengers risk of injury due to location within the vessel. Thereby, offering a significant Transfer of Innovation (TOI) from the automotive sector to the marine sector. Such analysis would be essential to inform the evacuation procedures on next generation 100m+ HSC.

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