Reliability-Based Design Assessment of Offshore Inflatable Barrier Structures made of Fibre-Reinforced Composites

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Abstract

Analysis and design of inflatable structures made of fibre reinforced composites have been the focus of many researchers in recent times. As with most designs, sources of uncertainty, variability and bias in the performance of the designed structures exist and should normally be assessed. This paper thus, seeks to identify and quantify levels of uncertainties that are in the design of a typical inflatable fender barrier structure against impact loadings and conducts reliability-based evaluation toward understanding safety levels and factors of safety to be employed for its design and for similar structures. Using a previously validated 3D parametric fluid-structure interaction analysis results of the model, implicit limit state response surface-based performance functions were derived for the structural responses to loads for the complex stresses and strain modes of failures. The First Order Reliability Method (FORM) was used to evaluate the influence of the uncertainties in materials and load parameters and hence the safety margins for the modes of failures considered. The findings in this study will provide benchmark levels for practicing engineers in carrying out optimal design of similar inflatable structures with acceptable safety levels.

Keywords: Inflatable Barriers; Safety margin; FORM; Fluid-Structure Interaction; Offshore structures

1.0 Introduction

Composite materials have found useful applications over the years in many structural systems due to their high specific stiffness, strength and resistance to corrosion among other valuable properties [1, 2]. They are employed in the aircraft, automobile, machinery and marine industries as well as in bridges, offshore and a host of other mechanical and civil engineering structures.

However, due to the inherent variability in the mechanical properties of composites and the wide variety of failure mechanisms following their complex structure and manufacturing processes; researchers have since acknowledged the need to incorporate uncertainties in engineering designs of the structures to adequately satisfy the need for safe and durable structures [3,4].

The traditional method in accounting for these uncertainties has been based on empirical approach where safety coefficients are employed to cover for the uncertainties in the composite materials and structural loads. This approach however, leads to introduction of invariant safety coefficients that are either too large, thus leading to conservative (high cost) structures or in some cases too small to guarantee safety and stability of the structure [4-6]. For example, Baley, *et al.,* [7] reported that safety factors of between 4 and 6 are used for static loads and up to 10 for dynamic loads in design of marine structures fabricated from FRP composites. This may lead to generous sizing/design that might affect wider utilization of the composite materials.

In contrast to the deterministic (traditional) approach, the probabilistic-based design method, which gives indication on how different design parameters influence the structural safety, are employed considering stochastic data in achieving an objective safety margin for the materials under prescribed loading conditions.

In civil, aerospace and marine engineering, utilization of fluid-structure interaction for performance enhancement and development of new schemes has been evolving and it is on the rise [8]. Due to the usual complex nature of these problems, numerical methods which mostly employ simplistic linear fluid and fluid-structure interaction models [8,9] are often used for their analyses with the common practice of using Allowable Stress Design Method (ASDM) for the design of the inflatable structures.

In Young *et al.,* [8], it was reported that the stochastic composite materials stiffness considered in the reliability-based design of self-adapting composite-marine propellers have marginal effects on the hydro-elastic behaviour of the self-twisting propellers. Carneiro *et al.*, [10] also reported that reliability index is sensitive to small variations in the thickness variable for ply-angle composite laminate structures even if the total weight of the structure is the same and Liu *et al.,* [11] recommended reliability based safety factor of 2.0 for metallic strip flexible pipes subjected to external pressure. While the general procedure for limit state designs and target reliabilities have been developed for concrete, masonry, steel, rigid composites and timber, the same cannot be said of inflatable structures where only a few studies have been reported [12].

This study proposes a pragmatic approach for the assessment of the influence of materials and loads uncertainties in reliability-based design for an inflatable offshore fender barrier structure made of a hyper-elastic composite, considering a relatively large number of random variables. The pneumatic structure operates on a relatively high inflation pressure and was assessed using finite elements numerical scheme considering large deformation causing geometric and constitutive nonlinearity.

This is important giving the unique nature of the materials, size, shape and loading conditions of the structure for objective based safety factors against critical failure modes of stress and strain with respect to the uncertainties considered and operation of the marine inflatable fender barrier structure.

The paper is structured as follows: Section 2 describes the inflatable structure under consideration, its components, the composite material and laboratory assessments and findings thereof. Section 3 describes the geometric and structural model of the inflatable fender barrier structure and the numerical analysis methods employed. Section 4 introduces the reader to the First Order Reliability Method (FORM). Section 5 presents the response surface methodology. Section 6 presents the methodology adopted for the reliability-based design of the inflatable structure. Section 7 Presents findings and discussions and Section 8 concludes on the findings in this paper.

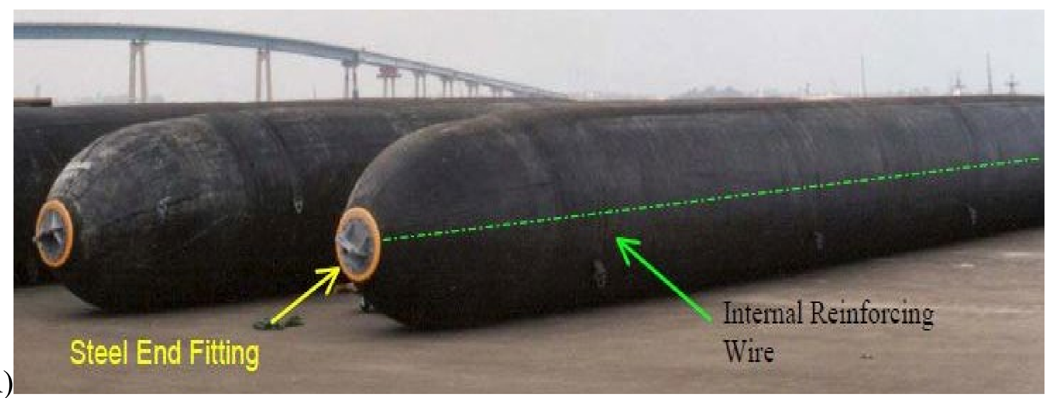
2. The Inflatable Offshore Fender Barrier Structure

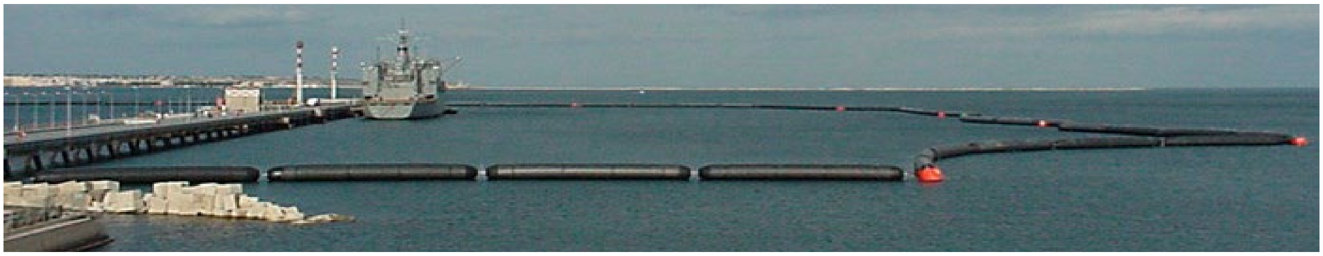
The inflatable offshore fender barriers are composite offshore structures that are traditionally installed at sea sites around valuable offshore assets (as shown in Figure 1) to prevent unauthorized access and limit deliberate actions of militants and terrorists that have led to considerable loss of billions of dollars of offshore investment around the globe [1].

The inflatable offshore barrier structure is a novel designed structure produced by Dunlop G.R.G. Holdings Ltd. UK and with structural capacity to limit access of intruding vessels as well as to withstand impact from certain vessels and environmental loadings of wind gust, ocean current and waves.

The Inflatable Offshore Fender Barrier Structure is made of neoprene-nylon reinforced composite, steel end-plate and internal steel bars connected to the end fitting plates as shown in Figure 1A.

(A)





(B)

Figure 1: A: Unit of the Inflatable Fender Barrier B: Typically Installed Inflatable Offshore Fender Barrier

2.1 Barrier carcasses of the Inflatable Offshore Barrier Structure

The barrier membrane is made of M006 barrier composites material made from neoprene polymer matrix and woven nylon (nylon 6.6) fibres with sections in warp and weft directions as shown in Figure 2 [1, 13].

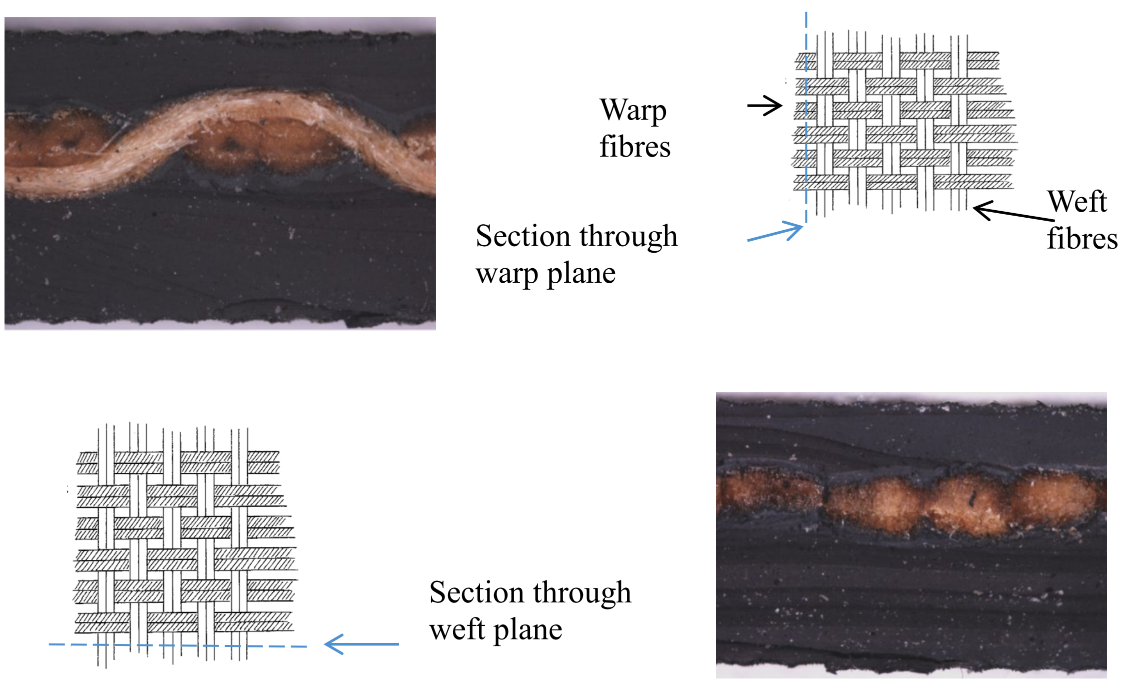


Figure 2: Section through the composite showing the warp and weft fibre reinforcements within the neoprene matrix

The structure of the inflatable fender barrier is constructed, such that, the composite reinforcement in the warp direction aligns to the longitudinal length of the barrier structure while the cap ends of the structure made of the composite have their fibre reinforcements oriented to the weft direction which corresponds to the circumferential direction of the structure.

Experimental assessments of the composite under uni-axial tension loading for sample strip specimens of 50 x 200 mm under varied testing temperatures of -4^{0}C, 20^{0}C, 35^{0}C and 55^{0}C indicate that the composites demonstrate anisotropic mechanical properties with average ultimate tensile strengths at 20 ^{0}C of 61.5 N/mm^2 and 47.72 N/mm^2 in the warp and weft directions respectively. Figures 3 and 4 show the stress-strain plots of the composite at 20^{0}C for seven (7) test specimens and summary of results for other testing temperatures considered are presented in Figures 5 and 6 where the results show a general reduction in stiffness of the composite material as the testing temperature increases beyond 20^{0}C.

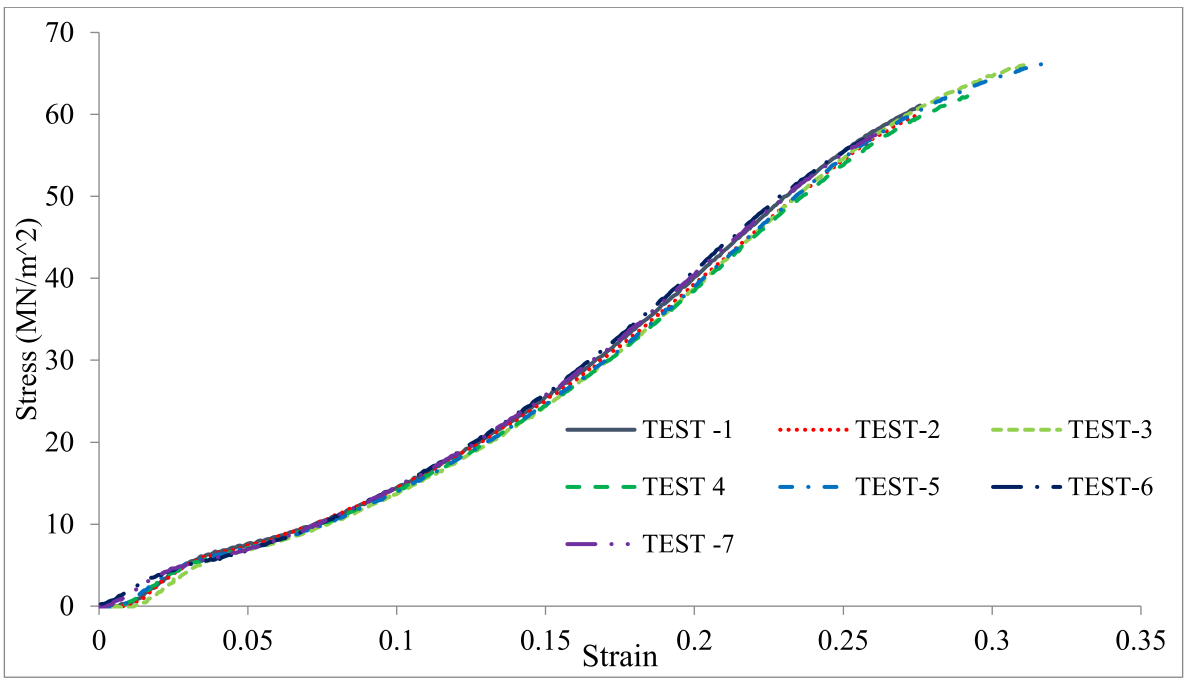


Figure 3: Uniaxial stress-strain relation for the composite oriented in the weft direction at 20^{0}C testing temperature for seven test specimens (1-7)

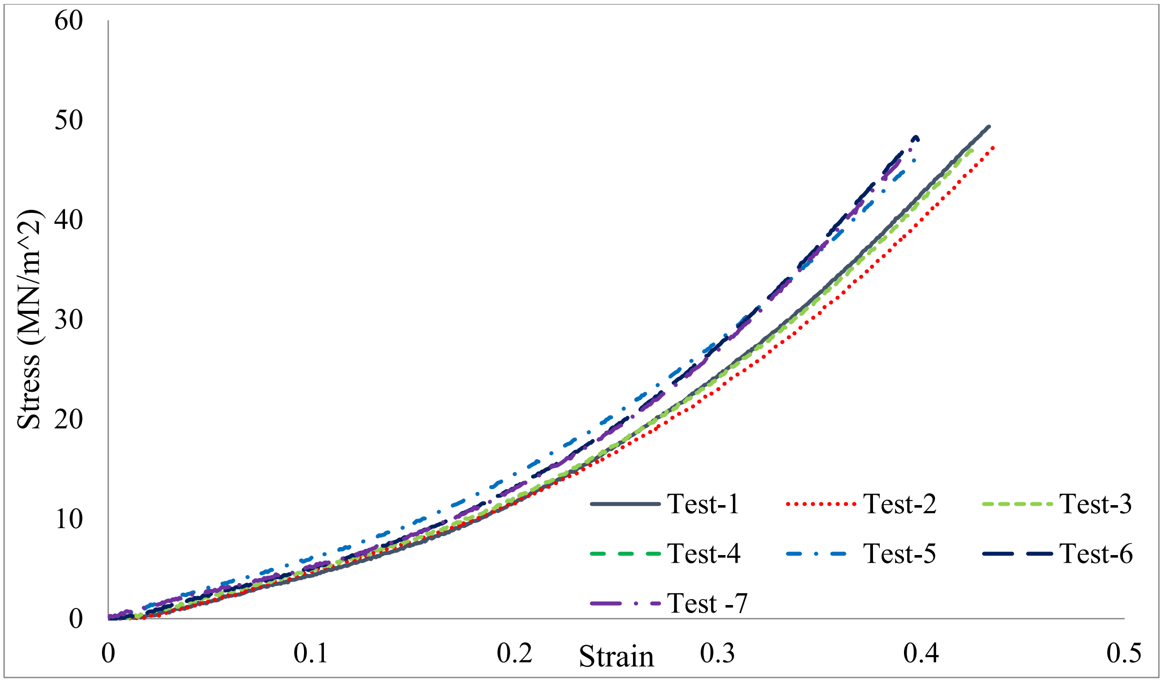


Figure 4: Uniaxial stress-strain relation for the composite oriented in the warp direction at 20^0C testing temperature for seven test specimens (1-7)

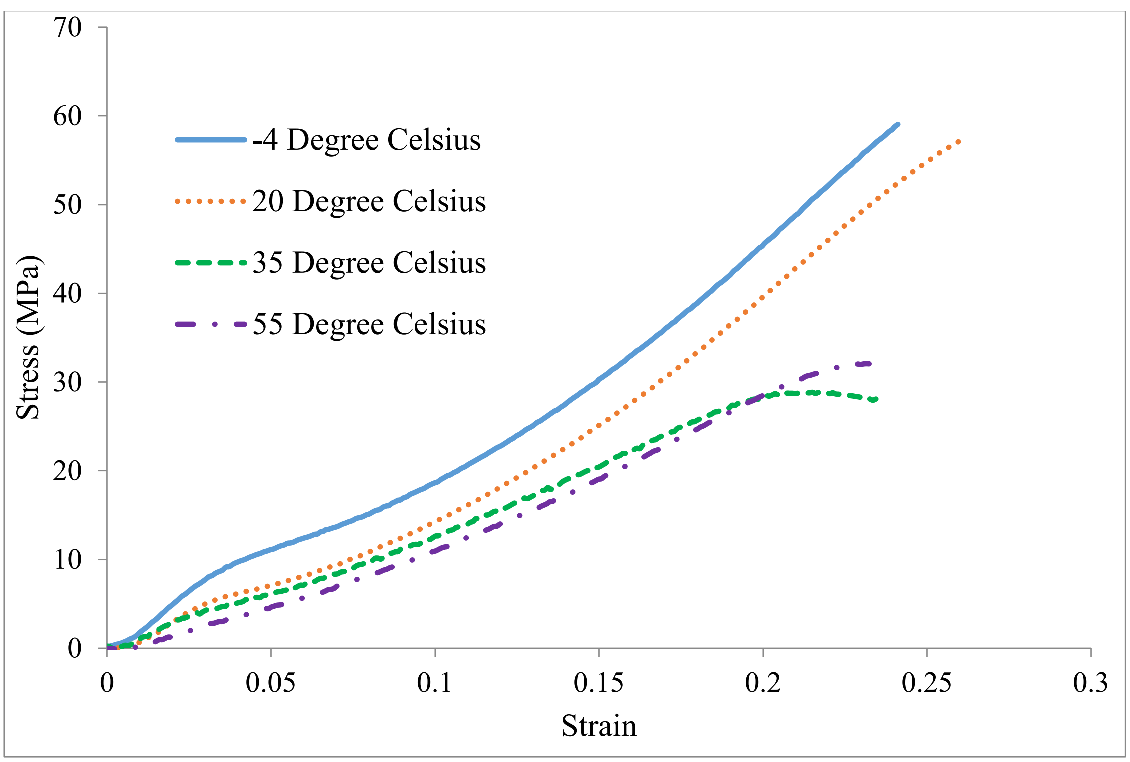


Figure 5 Uniaxial stress-strain plot of the composite at varying testing temperatures (weft direction)

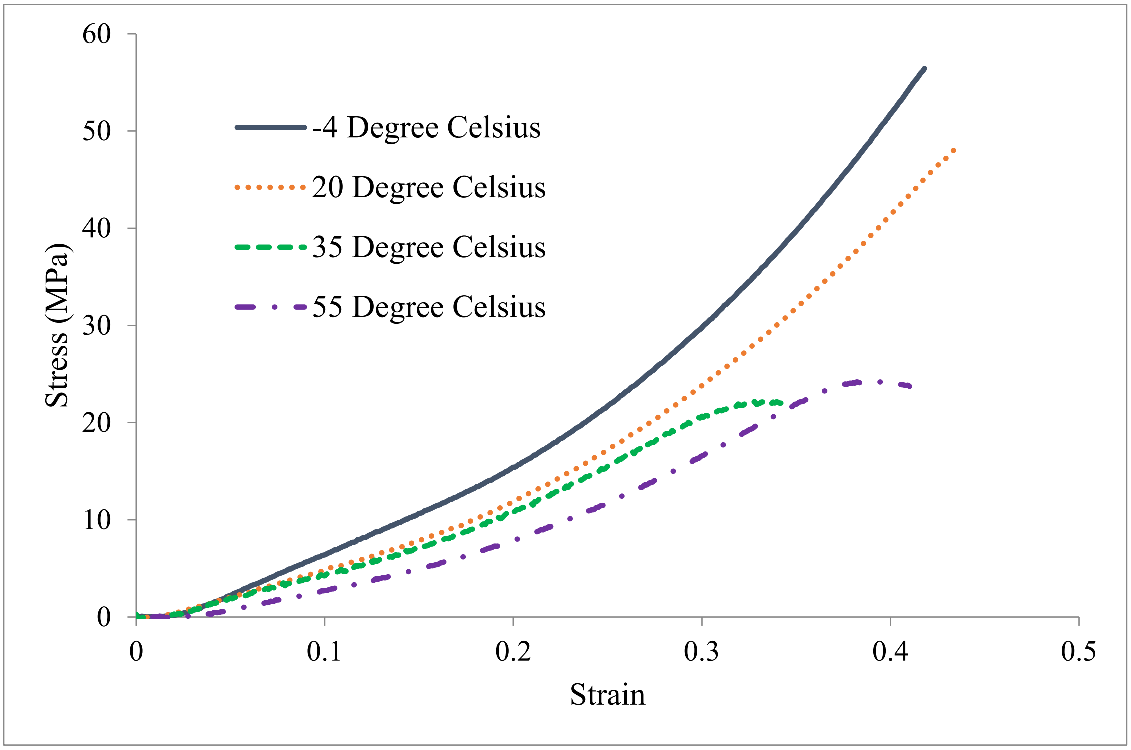


Figure 6: Uniaxial stress-strain plot of the composite at varying testing temperatures (warp direction)

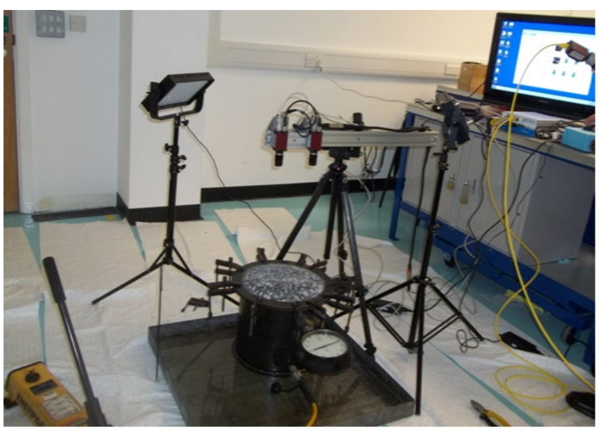


Figure 7: Inflation test set-up of the composite using Imetrum digital Imaging Correlation Equipment and Software[13]

To ascertain the multi-axial stress capacity of the composite, bulge/inflation tests were carried out as per the set up shown in Figure 7 [13]. A typical hydraulic fluid of density and viscosity of 857 kg/m^3 and 32 mm^2/s respectively, at the ISO standard reference temperature of 40^{0}C was used for continuous inflation of the composite to a pressure of 65 kPa. The tests were executed using a simple test rig made of 320 mm diameter cylindrical steel reservoir fitted with pressure gauge and a hydraulic pump for inflation of the composite membrane. The test is such that as the hydraulic pressure is increased, the pole displacement of the composite is measured using the Imetrum commercial 3D digital correlation software.

Findings from inflation test show that the composite can withstand inflation pressure of up to the 65 kPa which is well above the operating inflation pressure (7 kPa) of the barrier structure with a corresponding maximum displacement of 40 mm.

3. Geometric and Structural model of the Inflatable Fender Barrier

The geometric and structural models adopted for the analysis of the inflatable offshore fender barrier structure are as presented in Figure 8.

The barrier end plate fittings of the inflatable offshore barrier structure were made of mild steel plates of 0.6 m diameter and 0.01 m thickness. The modulus and density of the material are respectively, 205 GPa and 7850 kg/m^3. The internal reinforcements were made of 24 mm diameter wires with ultimate strength and elastic modulus of 991.94 MPa and 63.74 MPa respectively.

The response functions from impact loading of the High Speed Manoeuvring Surface Target (HSMST) vessel and the Offshore Racer (OR) vessel with the characteristic parameters presented in Table 1 were idealised.

Table 1: Typical parameters of the High Speed Manoeuvring Surface Target and Offshore Racer Vessel Considered [1]

Description	**HSMST**	**Offshore Racer**
Length (m)	7.239	11.582
Draught (m)	0.814	0.71
Beam (m)	2.743	2.743
Dead Weight (kg)	1837	3765
Impact speed (m/s)	13.4	24

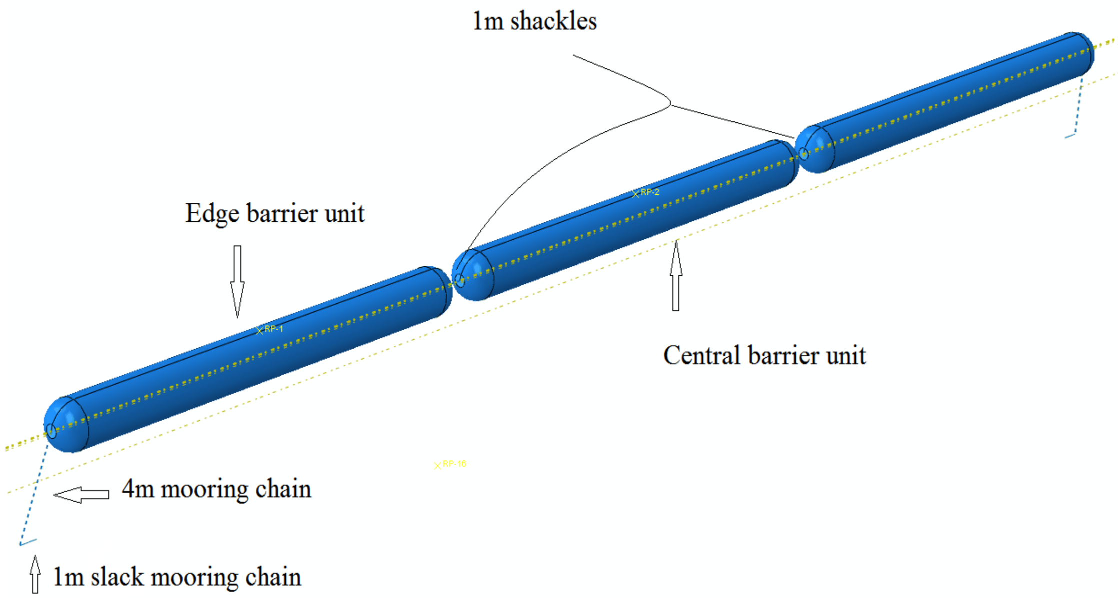


Figure 8: Geometric model of the inflatable barrier structure as a unit and shackled end to end.

The Coupled Eulerian-Lagrangian based formulation describing the governing differential equation for the problem reported in Aboshio & Ye [14] was utilized. This is presented here in Eq.(1), using the fluid structure coupling scheme shown in Figure 9.

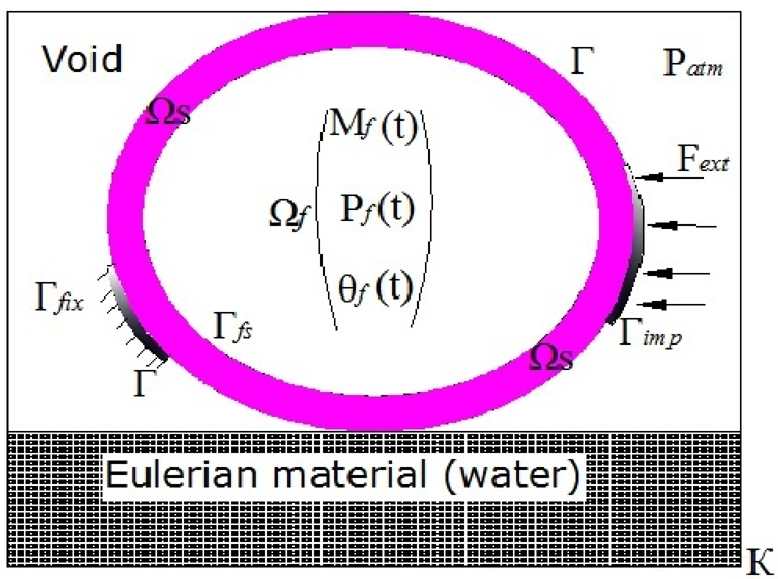


Figure 9: Model depicting the barrier, the surrounding water, the parameters describing the enclosed air pressure and boundary conditions of the structure (where m_f = mass of fluid, p_f = gauge pressure of fluid and the θ is the temperature of the fluid) [14].

In Fig.9, the Lagrangian domain, Γ, occupied by solid is denoted by Ω_s; the domain occupied by fluid is denoted by Ω_f and the direct fluid–structure interaction, (i.e where the structure interacts with the fluid – the internal part of the solid body) is denoted by $\Gamma_{fs} = \Omega_s \cap \Omega_f$. Γ_{fix} is the external boundary where displacement conditions are imposed and Γ_{imp} is where stress boundary conditions are specified as in Eq.(1).

$$\frac{D\emptyset}{Dt} = \frac{d\emptyset}{dt} + v.\Delta\emptyset \tag{1}$$

where $\emptyset$ is an arbitrary solution variable

v is the material velocity

Δ is the gradient operator

$\frac{D\emptyset}{Dt}$ is the materials time derivatives of $\emptyset$

$\frac{d\emptyset}{dt}$ is the spatial time derivatives of $\emptyset$

4. First Order Reliability Method

The First Order Reliability Method (FORM) is widely used in reliability-based analysis and design of structures. The method evaluates the performance function g(**X**), which is often a complex, nonlinear and multidimensional equation, by an approximate solution method via linearization or consideration of the first order Taylor expansion from which the reliability R, is computed based on the relation in Eq.(2).

$$R = 1 - P_f = P\{g(\boldsymbol{X}) > 0\} = \int_{g(\boldsymbol{X})>0} f_x(\boldsymbol{X})\, dx \tag{2}$$

where P_f is the probability of failure and $f_x(\boldsymbol{X})$ is the probability density function (PDF) of the variables.

The method is considered more efficient and simpler compared to alternative methods of evaluating the integral in Eq.(2)[15]. The simplification is achieved through transforming the random variables from their original random space **X** into standard normal space **U** based on the condition that the cumulative density functions (CDFs) of the random variables are the same before and after the transformation using the popular Resenblatt transformation [16].

The transformed standard normal variable is based on the relation in Eq.(3).

$$U_i = \Phi^{-1}\left[F_{x_i}(X_i)\right] \tag{3}$$

in which $\Phi(\cdot)$ is the standard normal cumulative distribution function and the joint PDF is the product of the individual PDFs of standard normal distribution presented in Eq.(4) in addition to the approximate integration boundary g(**U**) presented in Eq.(5).

The most probable point, MPP, being the point with the highest probability density on the performance g(**U**=0), as shown in Figure 10, is obtained using the optimization relation presented in Eq.(6). The minimum distance $\beta = \|\boldsymbol{u}^*\|$ is called the reliability index and is related to the probability of failure by the relation in Eq.(7).

$$\emptyset_u(\boldsymbol{U}) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{1}{2}{u^2}_i\right) \tag{4}$$

$$g(\boldsymbol{U}) \cong L(\boldsymbol{U}) = g(\boldsymbol{u}^*) + \nabla g(\boldsymbol{u}^*)(\boldsymbol{U} - \boldsymbol{u}^*)^T \tag{5}$$

$$\begin{cases} \max_{\boldsymbol{u}} \quad \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{1}{2}{u^2}_i\right) \\ \quad subject\ to\ g(\boldsymbol{u}) = \boldsymbol{0} \end{cases} \tag{6}$$

$$R = 1 - P_f = 1 - \Phi(-\beta) = \Phi(\beta) \tag{7}$$

where $L(\boldsymbol{U})$ is the linearized performance function, $\boldsymbol{u}^*$ is the expansion point and $\nabla g(\boldsymbol{u}^*)$ is the gradient of g(**U**)

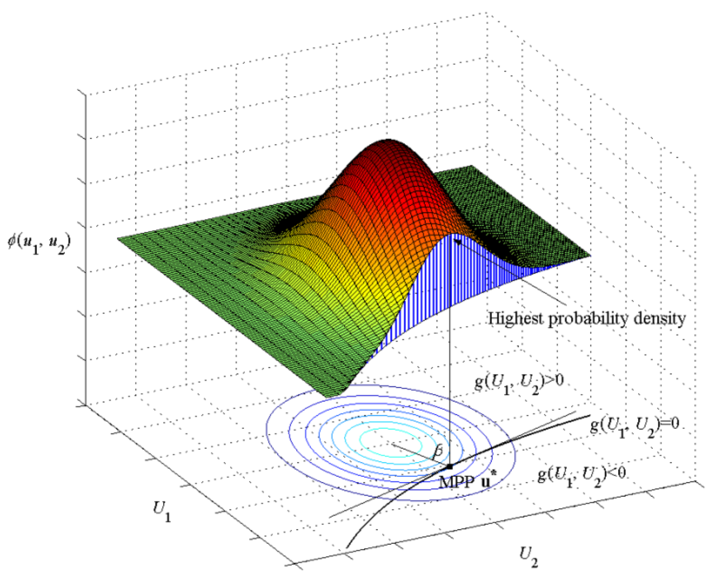


Figure 10: Typical Integration of the Probability Density Function after Transformation of the Random Variables to U space (Xiaoping Du [17])

To further reduce the computational cost of implementing the FORM, new and efficient algorithms and alternative approaches and forms for deriving the limit state function are introduced [3, 18, 19]. In relation to the studies on the limit state function, the response surface method (RSM), artificial neurons network (ANN) and genetic algorithms (GA) have been employed as suitable alternatives to traditional explicitly defined performance functions. The response surface methodology was used for the inflatable offshore fender barrier structure.

5. Response Surface Methodology

The response surface method (RSM) is widely used in reliability analysis. It transforms implicit limit state functions to explicit ones which are not necessarily the basic variables essential to the strength and resistance parameters defining the limit state function [20-22]. The basic formulation of RSM is based on regression analysis where an output quantity $g(\boldsymbol{X})$ that is related to a number of input variables $x_i, x_{ii}, \ldots x_n$, is assembled into a vector **x** by a functional relation f(), as presented in Eq.(8).

$$g(\boldsymbol{X}) = f(\boldsymbol{p}, \boldsymbol{x}) \tag{8}$$

where the vector **p** is a set of unknown parameters determined using the regression/least square analyses, from which a combination of linear term, linear and interaction terms and linear, interaction and quadratic terms are derived using Eq.(9).

$$g(\boldsymbol{X}) = p_0 + \left.\sum_{i=1}^{n} p_i x_i \quad {}_{linear}\right\} + \left.\sum_{i=1}^{n-1} \cdot \sum_{j=i+1}^{n} p_{ij} x_i x_j \quad {}_{interaction}\right\} + \left.\sum_{i=1}^{n} p_{ii} x_i^2 \quad {}_{quadratic}\right\} \tag{9}$$

6. Methodology for Reliability based Design of the Inflatable Offshore Fender Barrier Structure

First, deterministic parametric analyses of the inflatable offshore fender barrier structure subjected to impact loadings (at three locations per barrier element were considered: close to the supports (shackles ends)-right and left and at mid span of the structural model for both edge and the central barriers and for 6 and 7kPa inflation pressures of the barrier system) from vessels described in Table 1 were carried out using finite element models described in Section 3. The maximum stresses and strains from the parametric study and laboratory based results of the composite materials were obtained and thereafter fitted to standard statistical models of normal, log-normal and Weibull distributions to ascertain the best model fit for each data considered.

Using the response surface methodology described in Section 5 and considering the laboratory and analytical data, and the explicit limit state performance function; the First Order Reliability Method was carried out using a Matlab based code for the assessment of the reliability indices and probabilities of failure for a number of safety factors for the inflatable offshore fender barrier subjected to impact loadings.

The methodology employed in the reliability-based design of the inflatable offshore barrier structure is summarized in the flowchart presented in Figure 11.

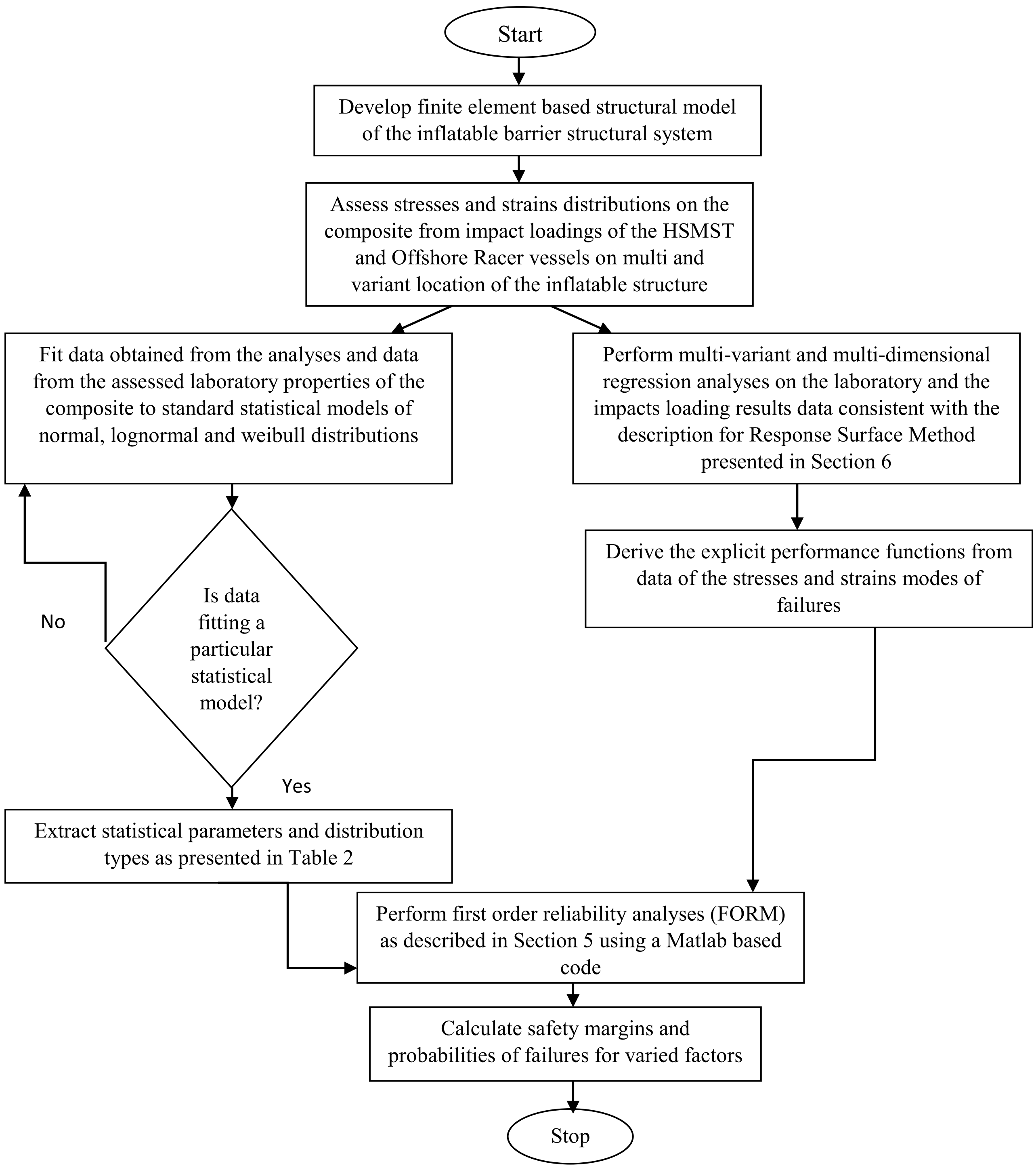


Figure 11: Flow chart describing methods employed for the reliability-based design of the barrier

7. Results and Discussion

Results of the laboratory based assessments of the neoprene-nylon fibre reinforced composite, stresses and strains as well as the parametric numerical study results of the response to impact loading of the inflatable barrier which were hitherto validated as reported in [1, 14 and 23] are presented in Table 2 (See Appendix I for sample output results). Stochastic models of the variables **(X)** (assumed to be mutually independent) with parameters and distributions fits for the varied impact loading responses are also presented in Table 2.

The performance function derived for failure modes in stress and strain using the response surface methodology are respectively given in Eqs.(10) and (11).

$$\delta_c - \delta_{ult} = (72.59 - 3.44x_1 + 0.016x_2x_1 - 0.055x_3x_1 + 59.81x_4 - 0.026x_5 - 0.0025x_1^2) - 61.5 \quad (10)$$

$$\varepsilon_c - \varepsilon_{ult} = (0.399 - 0.005x_1 + 0.0004x_2x_1 - 0.000016x_3x_1 - 0.084x_4 + x_1^2) - 0.37 \quad (11)$$

where the variables x_i (i=1-5) are respectively the composite thickness, primary and secondary moduli of elasticity, stress and strain responses to the impact loadings.

Table 2: Statistical parameters and distributions for the variable considered

Description	**Mean value**	**Standard Deviation**	**Coefficient of Variation**	**Distribution Type**
Composite thickness (t) (mm)	4	0.05	0.0125	Normal
Primary Modulus (E_1) (N/mm^2)	144.66	11.4	0.0790	Normal
Secondary Modulus (E_2) (N/mm^2)	295.50	18.4	0.0620	Lognormal
Stress (σ) at full impact of HSMST (N/mm^2)	13.65	2.1	0.1540	Lognormal
Strain (ε) at full impact of HSMST (N/mm^2)	0.14	0.09	0.6430	Lognormal
Stress (σ) at full impact of Offshore Racer (N/mm^2)	47.97	3.51	0.0730	Lognormal
Strain (ε) at full impact of Offshore Racer (N/mm^2)	0.21	0.12	0.05714	Lognormal

Using the First Order Reliability Method (FORM), reliability indices as well as probability of failure under stress and strain, modes of failure were determined. Figures 12 and 13 present the reliability indices and the corresponding probabilities of failure for different safety factors against stress failure mode of the composite material.

From the results, it can be seen that the safety indices under the stress mode of failure are generally high with corresponding very low probabilities of failure (i.e likelihood of the stress regime in the composite to be higher than the ultimate tensile strength). Results from both Figures 12 and 13 also show strong non-linear relationships between the safety factors and the corresponding probabilities of failure. The results further show that the safety factor in excess of 1.15 is not critical to improving the failure probability of the structure but will only lead to generous use of the material with attendant cost implications which could be inhibitive to wide application of the composite. The safety factor of 1.15 has a corresponding probability of failure of almost zero (3.5×10^{-15}) and a safety index (beta) of about 6.

From the reliability indices and failure probabilities of the structure under strain mode of failure; it can be said that the strain failure mode is critical. The reliability indices in this case are lower when compared to the stress mode of failure. Here a safety factor between 1.45 to 1.5 gave good reliability levels with corresponding safety indices of between 3.5 to 4.7 as can be seen from Figures 14 and 15. Safety values below 1.45 is thus critical to failure of the composite material due to high strain and thus safety value of 1.5 could be recommended for used in design of the inflatable barrier structure using the neoprene nylon reinforced composite.

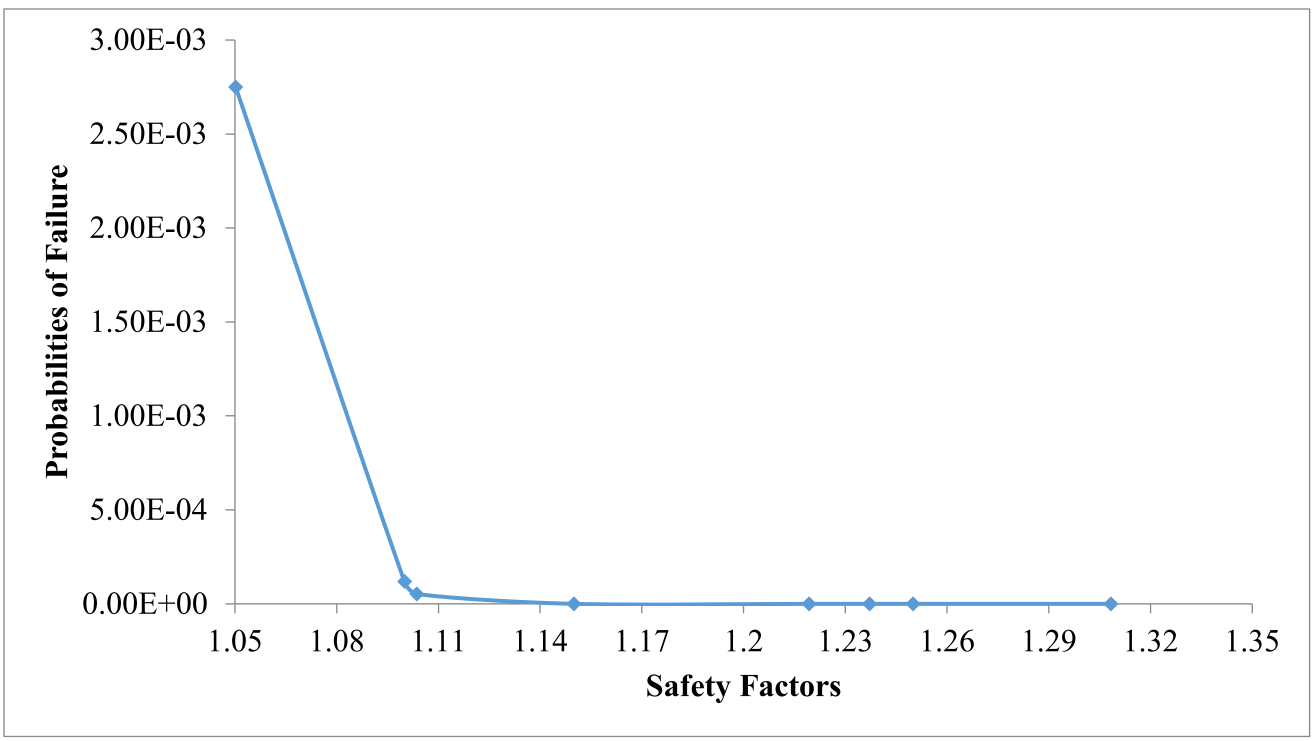


Figure 12: Probabilities of Failure for Varying Safety Factors against maximum stress in the composite

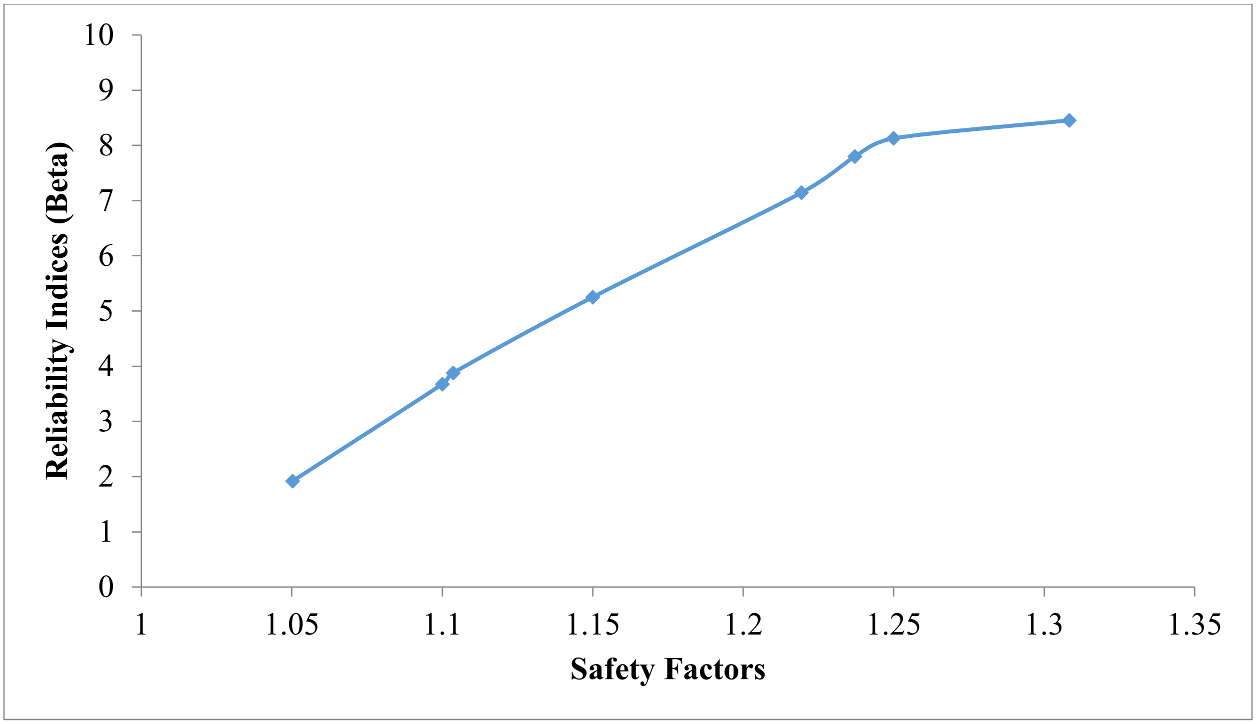


Figure 13: Safety Indices for Varying Safety Factors against maximum stress in the composite

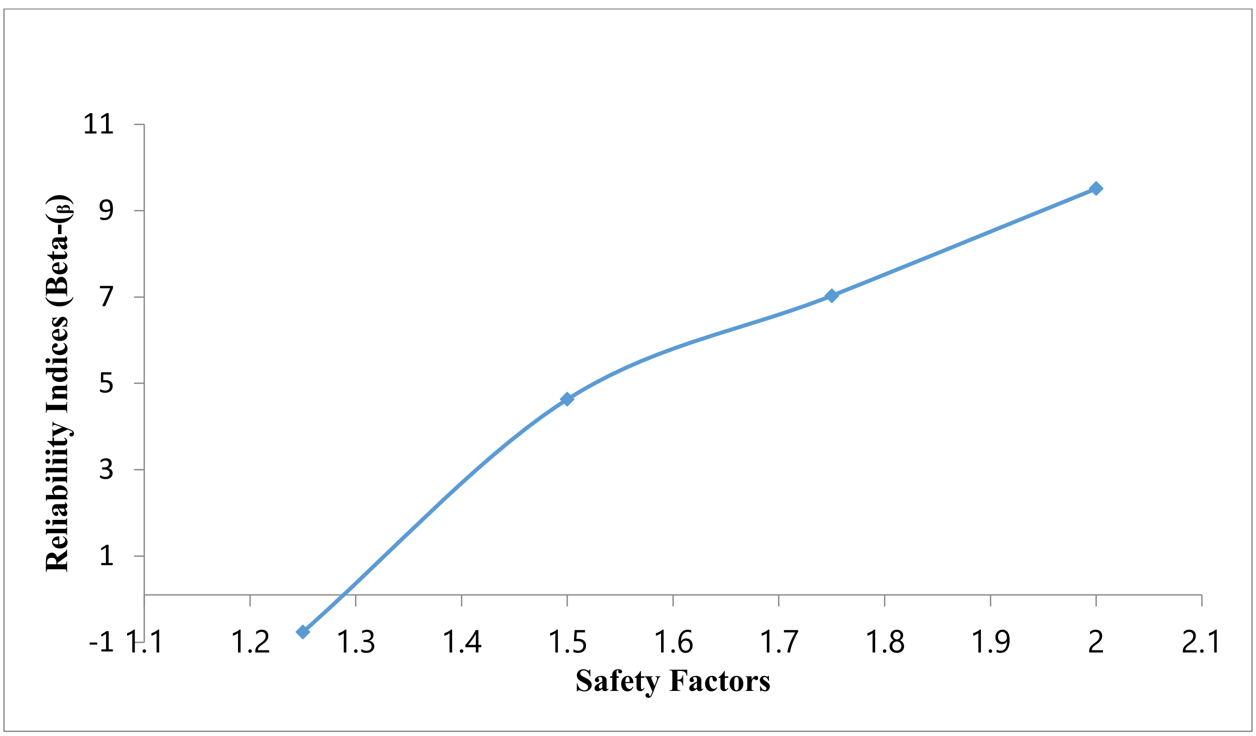


Figure 14: Safety Indices for Varying Safety Factors against maximum strain in the composite

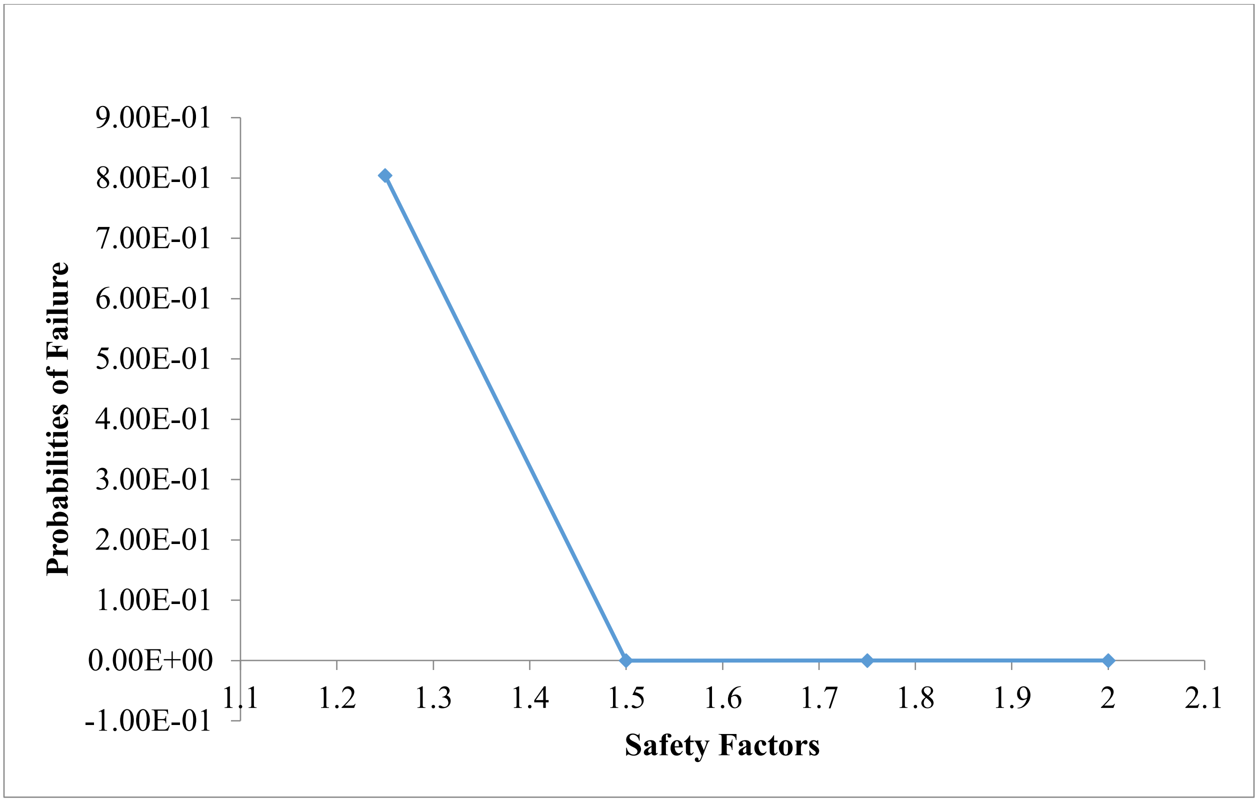


Figure 15: Probabilities of Failure for Varying Safety Factors against maximum strain in the composite

Sensitivity analysis, an indicator of the rate of change in the probability of failure (or reliability) due to changes in the design parameters are presented in Table 3. The results show that composite thickness and strain distribution (due to the high mean values) are more critical and have more impact on the reliability change than the other parameters considered.

Table 3: Sensitivity Analysis Results for Safety Factor of 1.5 against maximum strain of the composite

	Sensitivity of Failure Probability to distribution data		Sensitivity of Reliability Index to distribution data	
Parameter	Mean	Standard Deviation	Mean	Standard Deviation
t	-1.13E-05	1.04E-05	0.813410761	-0.7495019
E_1	9.04E-07	2.93E-06	-0.065072861	-0.2110597
E_2	3.62E-07	7.68E-07	-0.026029144	-0.0552593
ε	5.51E-05	0.00011896	-3.968282581	-8.5608932

8. Conclusion

In this paper, reliability analysis of a typical inflatable fender barrier operating at 20^{0}C and subjected to impact loadings was implemented using the response surface method and first order reliability method (FORM) with a view to come-up with an objective (cost effective) reliability based safety factors for the design of the offshore fender barriers and similar marine structures subject to impact loadings. From the study, the following conclusions can be made:

The safety level of the structure subjected to impact from HSMST vessel and offshore racer is most critical under strain rather than stress modes of failure.

The safety factor for the design of the inflatable barrier using the neoprene woven nylon composite against maximum stress can be limited to 1.15 with a probability of failure of 3.5 x 10^{-15}. When it is against maximum strain, the safety factor is 1.5 with a probability of failure of 2.94 x 10^{-6}.

Sensitivity analyses indicate that composite thickness and strain distributions at full impact are the most critical parameters to the structure's safety levels. Hence safety factor of 1.5 is recommended for the design of the inflatable fender barrier structure and similar structures made from neoprene-woven nylon reinforced composites

Acknowledgment

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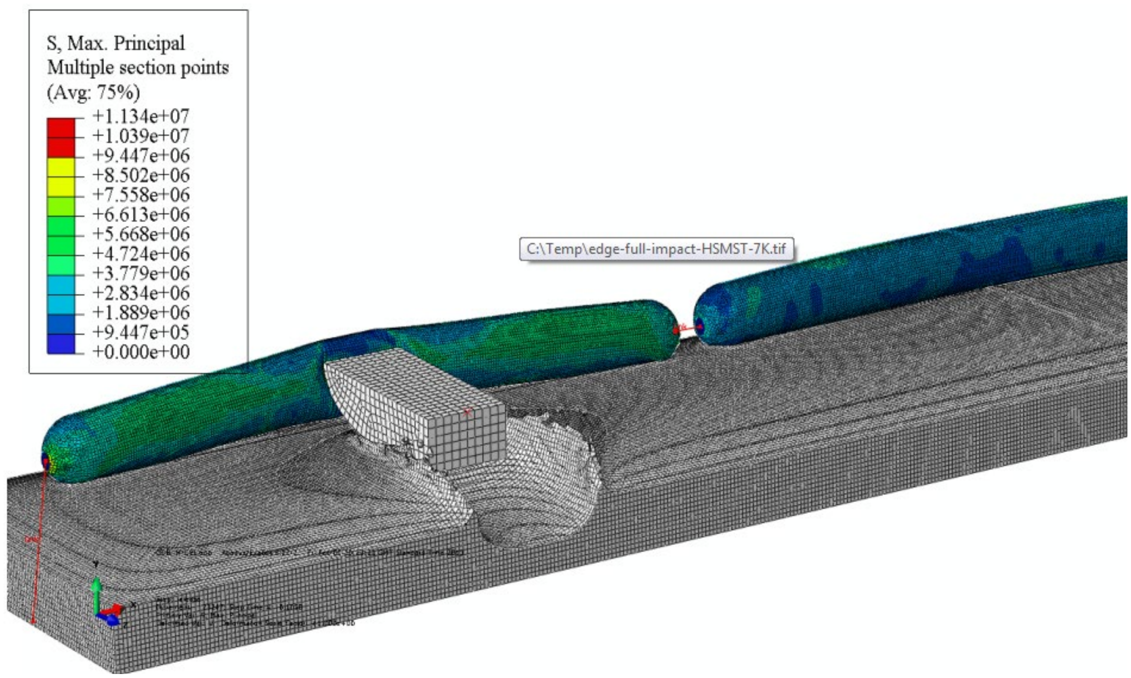
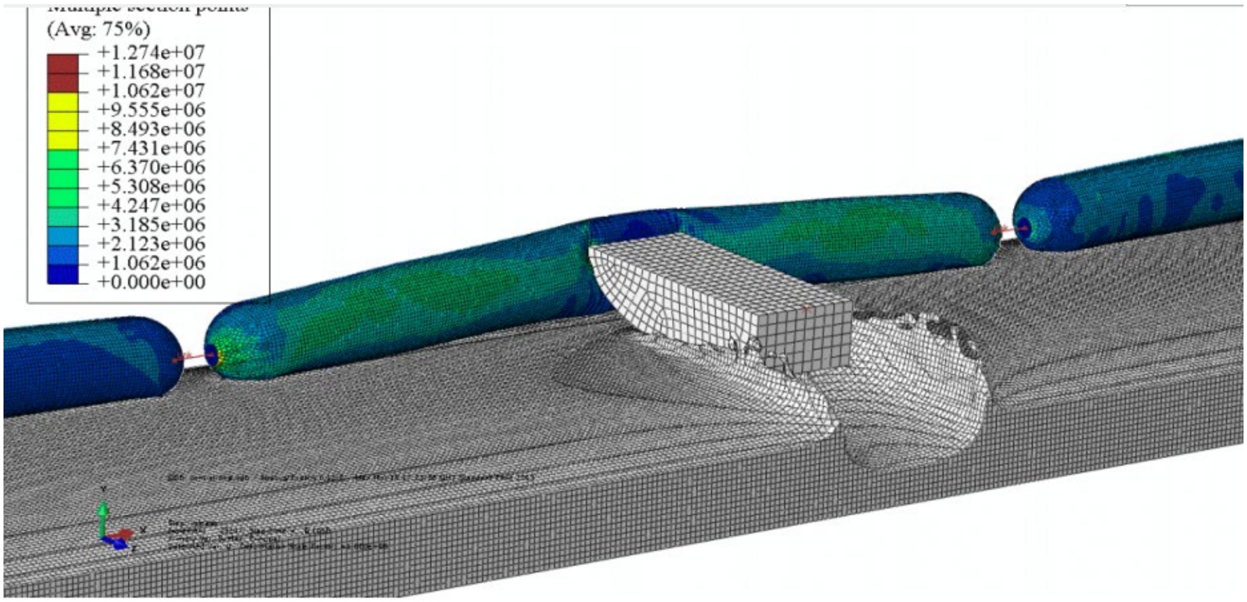
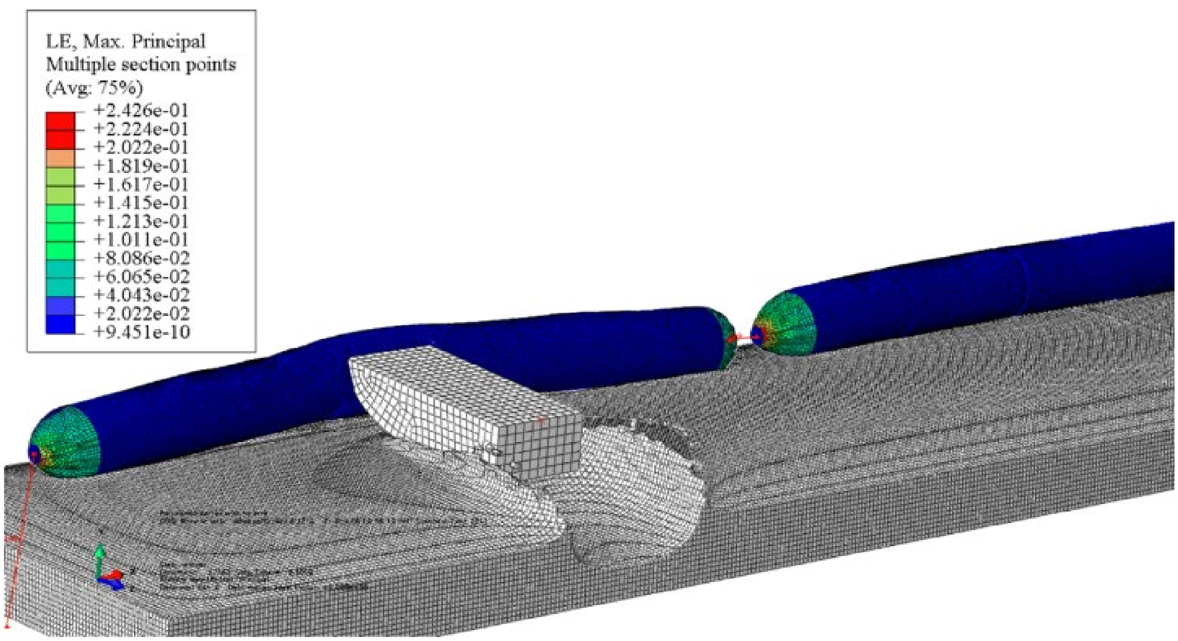
Appendix I



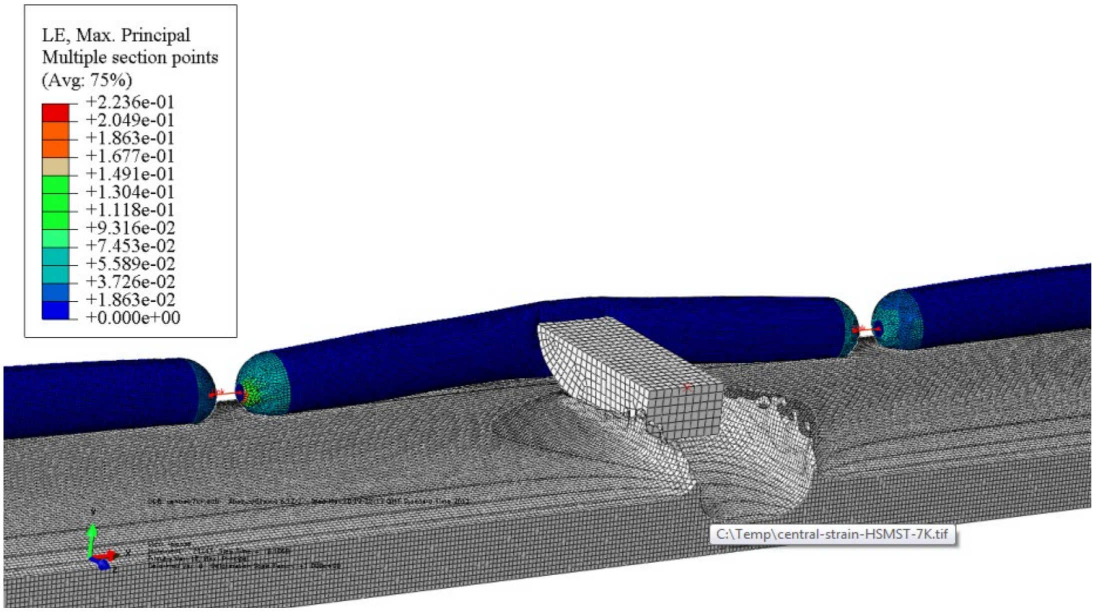
Stress distribution following the HSMST full impact on the edge barrier with initial inflation pressure of 7 kPa



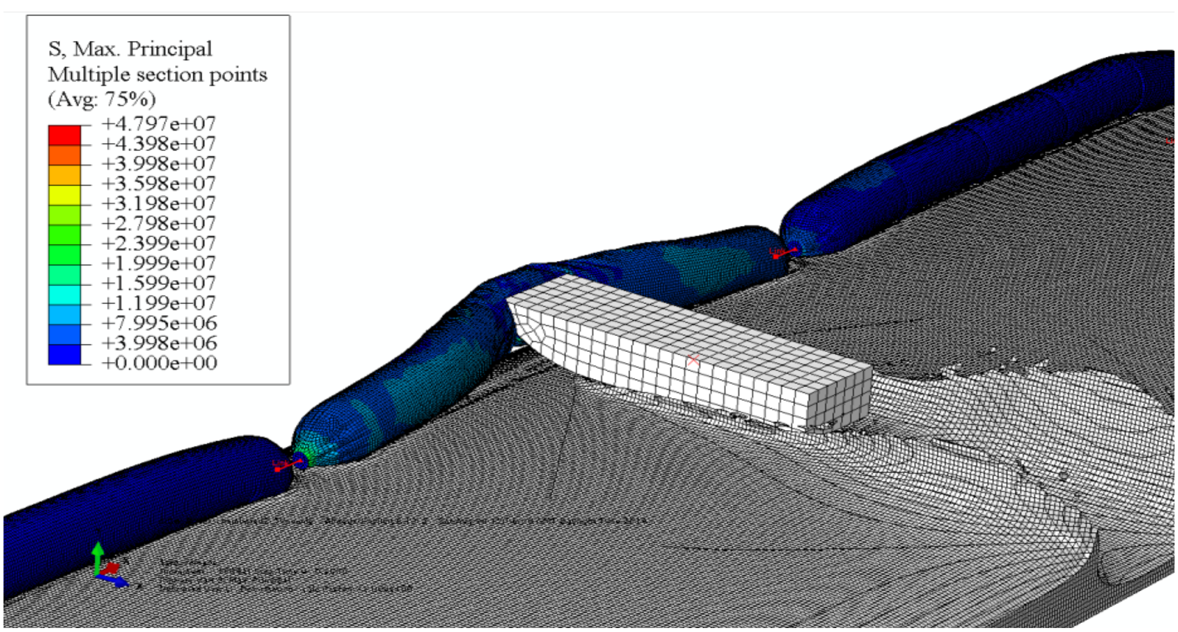
Stress distribution following the HSMST full impact on the central barrier with initial inflation pressure of 7 kPa



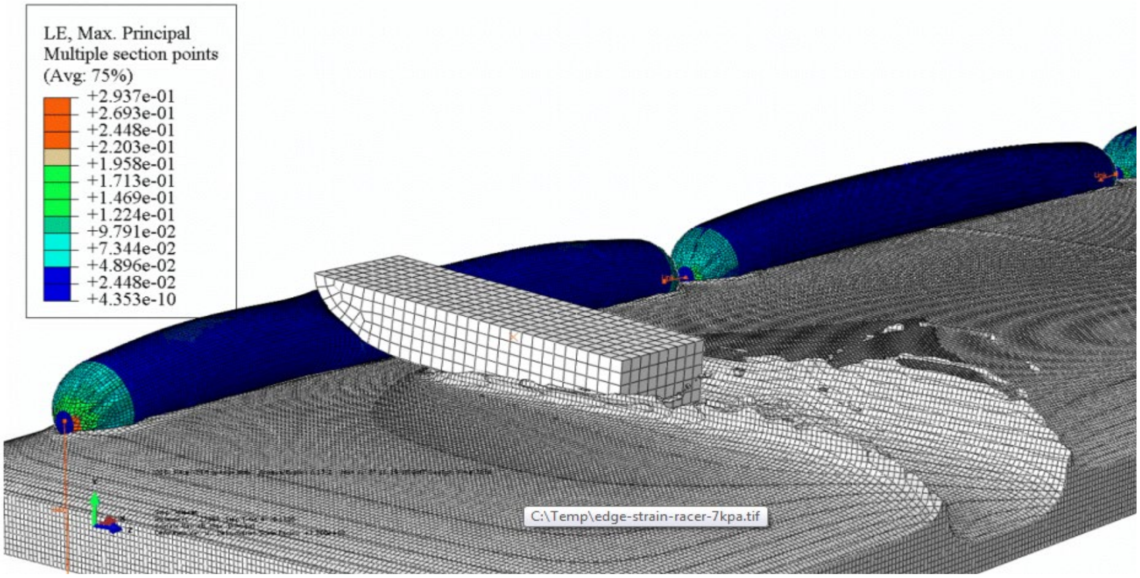
Logarithmic strain distribution following HSMST full impact on the edge barrier with initial inflation pressure of 7 kPa



Logarithmic strain distribution following HSMST full impact on the central barrier with initial inflation pressure of 7 kPa



Stress distribution following the offshore racer full impact on the central barrier with initial inflation pressure of 7 kPa



Logarithmic strain distribution following the offshore racer full impact on the edge barrier with initial inflation pressure of 7 kPa