

Evaluation of Surrogate Models of Internal Energy Absorbed by Oil Tanker Structure during Collision

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Abstract

The main purpose of the research presented in this paper is to evaluate the quality of surrogate models of collision energy absorbed by an oil tanker during collision accident, in order to evaluate appropriateness of their usage in a ship structural optimization process. The motivation for research is investigation of possibility to include ship crashworthiness as an additional objective in a ship structural optimization in a preliminary or even a concept design phase. Numerical simulations were executed in LS Dyna using simulation models generated by an in-house made model generator.

1. Introduction

Modern optimization methods, developed in the areas of naval architecture, aerospace, mechanical engineering etc. are capable of validating innovative vessels concepts as well as generating competitive designs for standard ship types. *ISSC (2012)* report contains a section on the design requirements, mathematical models of required fidelity for design phases (concept, preliminary and detail), basic taxonomy, applicable optimization methods, formulations including safety as design objective etc. The methods presented help designers to achieve significant savings for the shipyard and the ship owner: increase of deadweight; decrease in the price and weight of construction steel; production costs and lead time improvements; increase of safety (and robustness); savings regarding life cycle cost (LCC) etc.

As shown in *Zanic et al. (2013)*, numerical analysis methods for contemporary complex engineering systems, like CFD or FEM, can be computationally very demanding and despite of steady advances in computing power, the expense of running many analysis calculations remains nontrivial. Single analysis of one design solution can take from seconds to hours or even much longer for e.g. non-laminar and non-stationary 3D CFD problems. Therefore, direct use of some analysis methods is not possible in optimization because optimization demands several hundreds or even thousands analysis of different variants. To address such a challenge, surrogate or metamodeling techniques are often used. An application of surrogate modeling as approximations of expensive computer analysis codes can result in significant savings in both number of analysis and total time in which satisfactory optimal solutions are obtained. Due to the wide usage of this approach in many research fields, it can be found under various names like: surrogate (or metamodel) assisted optimization, surrogate (or metamodel) driven design optimization, surrogate (or metamodel) based design optimization, optimization using surrogate models (or metamodels), etc.

There are various criteria that can be used for assessment of the effects of optimization in designing ship and offshore structures. An optimally shaped structure can be compared to a design made by an experienced designer. For a certain typical simple structures, the optimization effects amount to a few percent, whereas for more complex and untypical structures such effects may amount to a dozen or so percent.

One of the main objectives of the national research project DATAS (www.fsb.unizg.hr/datas), is to investigate possible improvements in tanker structural design that could lead to the reduction of consequences for tanker ship accidents in Adriatic Sea. Of course the, the improved methodology for the tanker structural design needs to be incorporated in the ship design methodology and as such it is under the time constraints relevant to the ship design process, which can range from several weeks to several months.

Overall objective of a standard oil tanker structural design process is to simultaneously increase the ship-owner's profit and reduce shipyard production cost, while satisfying all rules prescribed by IACS Harmonized Common Structural Rules for Bulklers and Oil Tankers. The goal of DATAS project is to investigate possibilities of introducing additional structural safety measures as additional objectives. The primary focus is on the measures capable of identification of hull structural integrity (ship crashworthiness, hull girder ultimate strength). Selected design parameters, having significant effect on design solution, have to be identified and discussed with the stake-holders as a part of DeSS formulated for concept (CDP) and preliminary (PDP) design phases, where the most far-reaching decisions are made.

Outline of the proposed overall procedure is shown in Fig 1. The first three blocks are part of CDP, while the last is PDP. The main purpose of the Block 1 is a generation of the response surface model of internal energy E_i absorbed during collision as a measure of crashworthiness. The second block is used to perform multi-objective optimization with weight and structural safety measures (crashworthiness, hull girder ultimate strength) as objectives. The optimization will be done with constraints/requirements prescribed by the CSR Harmonized Rules for Bulklers and Oil Tankers. Block 3, where the preliminary design variant is selected from the set of non-dominated solutions, is the last block in CDP, but it could also be seen as a first block in PDP. The three hold FEM model is used in Block 4 to verify accuracy of the CDP model, and to dimension parts of structure like transverse bulkheads and double bottom that cannot be adequately dimensioned with the models used in CDP.

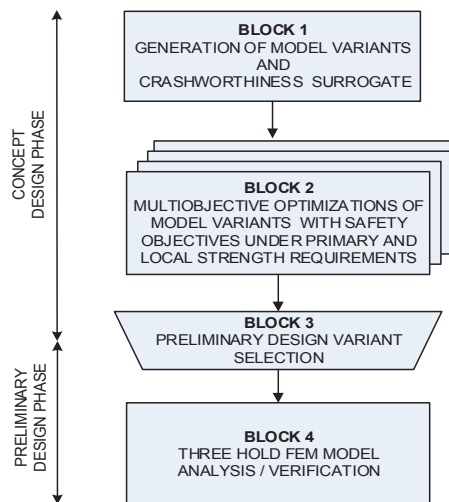


Fig. 1: Proposed tanker structural design procedure

The main purpose of the research presented in this paper is to evaluate the quality of surrogate models of internal energy absorbed by an oil tanker during collision accidents, in order to evaluate appropriateness of their usage in a ship structural optimization process. The motivation for that is an investigation of possibility of inclusion of ship crashworthiness measure as an additional objective in a ship structural optimization in a preliminary or even a concept design phase.

Crashworthiness (collision and grounding) analysis models are one of the most complex and the most time consuming ship structural analysis models. Depending on the level of details modeled and the extent of the model (partial model to full ship model), nonlinear finite element analysis of a single variant could take from an hour to several days. Even the simplest possible model are usually too demanding for direct usage in structural optimization during preliminary design phase and especially during a concept design phase.

The possible solution is a creation of appropriate surrogate models that could replace demanding nonlinear numerical models in structural optimization. Since an inclusion of surrogate models in optimization process requires execution of analysis runs that are necessary to train those surrogates,

special considerations are necessary to reduce number of analysis runs for the training to an acceptable level, while maintaining a level of accuracy acceptable for the optimization process.

2. Surrogate modelling

Surrogate / approximation / metamodeling, is the key to surrogate assisted optimization. It can be stated that surrogate modelling actually evolves from classical Design of Experiments (DOE) theory, in which polynomial functions are used as response surfaces, or surrogate models. One of the most cited handbooks with detail overview of DOE for classical (physical) experiments is *Montgomery (2001)*, while the overview of surrogate modeling for deterministic computer experiments (DACE – design and analysis of computer experiments) can be found in e.g. *Fang et al. (2006)*, *Simpson et al. (2001)*.

The main difference between “classical” and computer experiments is nonexistence of random error for deterministic computer experiments, which according to *Sacks et al. (1989)* leads to the conclusion that surrogate model adequacy is determined solely by systematic bias and that the classical notions of experimental blocking, replication and randomization are irrelevant. In depth review of surrogate modeling for computer based engineering design can be found in *Simpson et al. (2001)* and *Wang and Shan (2007)*. Steps necessary for generation of surrogate models includes: planning of experiments or sampling, Fig. 2, execution of simulations with original analysis methods, generation or creation of selected surrogate model and validation of surrogate model adequacy.

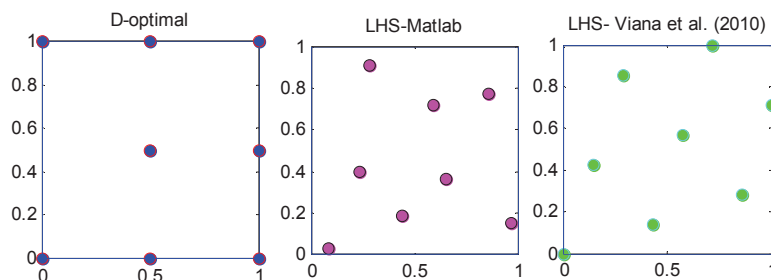


Fig. 2: Preview of D-optimal design and two different space filling LHS designs

After selecting an appropriate experimental design according to appropriate criteria, *Goel et al. (2008)*, *Viana et al. (2010)*, and performing the necessary computer runs, the next step is to choose a surrogate model type and corresponding fitting method. Many alternative models and methods exist, and there is no clear answer which is better. The selection of appropriate surrogate model depends mostly on characteristic of physical phenomenon that is approximated. Some of widely used surrogate models in engineering include: Response Surfaces (RS), *Fang et al. (2006)*, *Kaufman et al. (1996)*, *Montgomery (2001)*, *Roux et al. (1996)*, Kriging, *Koch et al. (2002)*, *Martin and Simpson (2005)*, *Simpson et al. (2001)*, Radial basis functions (RBF), *Fang et al. (2006)*, *Powell (1992)*, *Regis and Shoemaker (2007)*, Artificial Neural Network (ANN), *Miralbes and Castejon (2012)*, *Park et al. (2013)*, *Patnaik et al. (2005)*, Support Vector Machine (SVM), *Collobert and Bengio (2001)*, *Rivas-Perea et al. (2013)*, Multivariate Adaptive Regression Splines (MARS), *Friedman (1991)*.

Generally, the value of a target criteria response y at some location x can be written as:

$$y(\mathbf{x}) = \hat{y}(\mathbf{x}) + \varepsilon_b \quad (1)$$

where $\hat{y}(\mathbf{x})$ is surrogate model of response y , while ε_b is a surrogate model error or bias. As already stated, one of the characteristics of deterministic computer experiments is nonexistence of random error ε_r , and that is the reason why it is not included in Eq.(1).

In this research, RS method will be used as surrogate modelling method, so it's basic theoretical background is given in the following subchapter

2.1. Response surfaces (RS)

Probably the most widely used surrogate modeling method is response surfaces (RS) that approximates criteria functions using low order polynomials, mostly simple linear and quadratic or some specific polynomials like orthogonal Legendres polynomials.

General matrix formulation of this model can be written as:

$$\hat{y}_{RS} = \mathbf{B}^T \boldsymbol{\beta} \quad (2)$$

where \mathbf{B} is a k-tuple of a used polynomial functions, while $\boldsymbol{\beta}$ is a k-tuple of unknown corresponding coefficients. If a mostly linear polynomial is used, \mathbf{B} i $\boldsymbol{\beta}$ are:

$$\mathbf{B}^T = \{1 \quad x_1 \dots \quad x_i \dots \quad x_k\} \quad (3)$$

$$\boldsymbol{\beta}^T = \{\beta_0 \quad \beta_1 \dots \quad \beta_i \dots \quad \beta_k\} \quad (4)$$

The unknown coefficients $\boldsymbol{\beta}$ are usually determined using least square regression analysis by fitting the response surface approximation into existing data:

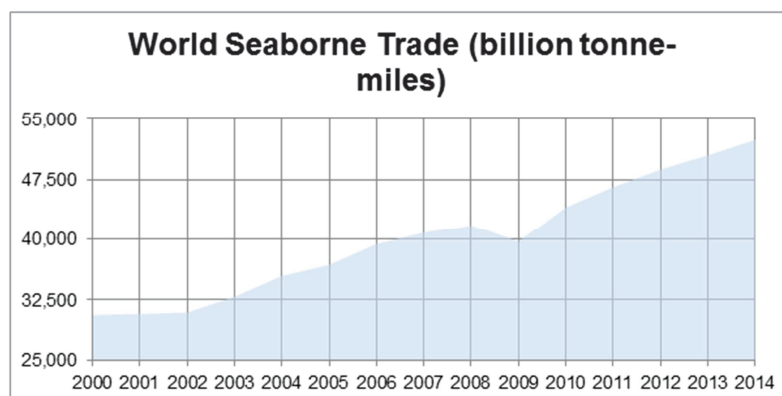
$$\boldsymbol{\beta} = (\mathbf{B}_{1-n} \mathbf{B}_{1-n}^T)^{-1} \mathbf{B}_{1-n} \mathbf{y}_{1-n} \quad (5)$$

where \mathbf{y}_{1-n} is n-tuple of n known response values, while \mathbf{B}_{1-n} is $k \times n$ matrix with the calculated values of selected basis functions at locations 1- n .

RS popularity for modeling of a deterministic computer experiments, besides its good characteristics for certain type of problems, is due to the fact that surrogate modeling itself evolves from classical Design of Experiments theory where RS was used for the description of physical phenomena, *Montgomery (2001)*. Discussion of the statistical pitfalls associated with the application of RS to deterministic computer experiments can be found in *Sacks et al. (1989)* and *Simpson et al. (2001)*. Some of the applications in engineering includes: structural optimization, *Arai and Shimizu (2001)*, *Prebeg (2014)*, *Vitali et al. (2002)*, and Pareto front generation, *Goel et al. (2007)*, *Lian and Liou (2005)*.

2. NFEM ship collision analysis

Ship collisions are high-energy marine accidents leading sometimes to catastrophic consequences: loss of human lives, loss of a cargo or a ship itself and environmental pollution on which closed seas are extremely sensitive. Due to that, a number of measures were taken to prevent or reduce the consequences of ship collisions and groundings. However, such accidents still occur worldwide.



Source: UNCTAD Review of Maritime Transport, 2014

Fig. 3: World Seaborne Trade, www.ics-shipping.org

It was in 1987 when one of the most catastrophic collisions occurred when "MT Vector", carrying 8800 barrels of gasoline collided with "MV Doña Paz" off the coast of Dumali Point, Mindoro, in the Philippines. More than 4000 people died in that incident, becoming so the deadliest ferry disaster ev-

er. More recently, on January 2012, the "Costa Concordia" collided with the rock formation near the coast of Isla del Giglio and grounded nearby. Due to the size of damage 32 people lost their lives and a ship was completely lost. A number of collision and grounding events occur during the year but, fortunately, the catastrophic events are rare and their number is being constantly reduced. On the other hand, maritime traffic is increasing and the number of ships transporting goods worldwide is growing, Fig. 3, and so is the risk of collision.

2.1 Adriatic Sea collision scenario

Adriatic Sea is a semi-enclosed narrow sea stretching from north-west to south-east mainly between two countries, Italy and Croatia. Other countries having the access to Adriatic Seas are all on its east coast: Slovenia, Bosnia and Hercegovina, Montenegro and Albania. The closest point between Italy and Albania defines the Otrant Strait which is the only entrance to the Adriatic Sea from the Mediterranean Sea. In this way, Adriatic Sea is rather closed sea and any risk of ship collision and related marine environment pollution in that area has to be considered seriously as the regenerating capacity of the sea is limited and the impact on surrounding industry, particularly tourism, may be dramatic.

Due to shape of the Sea two most important traffic routes are north-west to south-east or longitudinal routes and west to east, or transversal routes, Fig. 4. Commonly large merchant ships are sailing over longitudinal routes to bring the cargo to large northern harbours in Koper, Rijeka, Trieste, Venice etc. while ferries and leisure ships are sailing over transversal routes, connecting large cities on both west and east coast of Adriatic. Due to the nature of such trafficking an orthogonal collision of a tanker and a ferry was assumed to be a reasonable collision scenario for Adriatic.



Fig. 4: Maritime traffic in the Adriatic, *Zec et al. (2009)*

2.1 Numerical model

In order to study consequences of specified collision scenario a calculation model in commercial software package LS-Dyna was set. It consists of two ships in concern:

- A struck ship, being an Aframax class tanker
- A striking ship, being a typical international ferry of the Adriatic Sea.

Due to the complexity of the problem, both ship models are reduced in order to enable the study of all most important physical aspects of their collision and yet at the same time to enable the reasonably fast calculation. The main struck and striking ship particulars are listed in Table 1.

Table 1: Main struck and striking ship particulars

Struck ship (tanker)		Striking ship (ferry)	
Lpp	236 m	Length over all	121.83 m
B	42 m	Ship mass	4730 t
D	21 m	Ship with cargo mass (assumed)	6889 t
Scantling draught	15.1 m	Draft aft	5.25 m
Displacement	133000 t	Draft fore	5.30 m
Max. service speed	15.3 kn	Middle draft	5.28 m
Long. center of gravity (from L/2)	5.599 m	Ship centre of gravity height	8.38 m
Ship center of gravity height	12.050 m	Ship centre of gravity length	61.08 m

Struck ship model is being generated using an in-house software code enabling the quick generation of FE models by changing their geometric parameters like double side width, number of web frames, number and position of side stringers, etc. Since fine mesh is required in the collision zone the size of the finite elements in that area is approx. 100x100 mm. Struck ship model consists of the portside cargo hold and it is entirely made of fine mesh plate finite elements. The rest of the ship is taken into account by the concentrated ship mass (less the portside cargo hold) modelled using eight solid elements and located at the exact location of the ship centre of gravity.

Striking ship model is made in detail in the bow section while the rest of the ship is modelled using simple beam elements with appropriate mass. In this way, bow shape realistically affects the penetration in the struck ship side, while the rest of ship (inertia) is adequately taken into account. Finally, both models are presented in Fig.5, where the orthogonal collision scenario is set: portside cargo hold of a tanker is being subjected to the impact of a ferry bow.

The following scenario lists the reference collision scenario parameters:

- Ferry is located in front of the middle cargo hold of a tanker,
- Collision is orthogonal,
- Speed of a tanker is 0 m/s,
- Speed of the ferry is 8 m/s,
- Draft of the tanker is 15.1 m,
- Draft of the ferry is 5.3m.

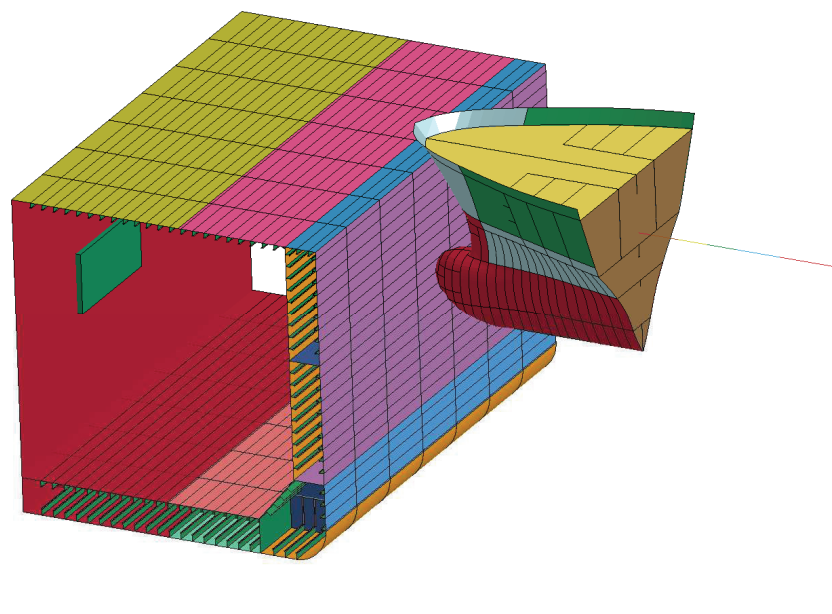


Fig. 5: Calculation model: portside cargo hold of a tanker and a ferry bow in orthogonal collision

2.3 Numerical analysis

FEM analysis is being performed using explicit LS-Dyna solver considering both non-linear material model properties and a contact between the models. Mesh size parameter is taken into account by applying Peschmann method of correcting the failure criteria, i.e. critical strain. Contact between the striking and the struck ship is defined using LS-Dyna keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. Both static and dynamic friction is defined for steel-to-steel situation and chosen values are 0.74 and 0.57, respectively. Material models used for ship models are defined by keywords *MAT_RIGID and *MAT_PIECEWISE_LINEAR_PLASTICITY.

As a result of collision a typical structural damage occurs as presented in Fig. 6. In all of the collision calculations, one for each variation of struck ship structural parameters, a tanker hull is breached, suggesting that impact of such energy would lead to cargo spill. Two main sets of data characterise collision event, namely contact force and deformation energy (both elastic and plastic).

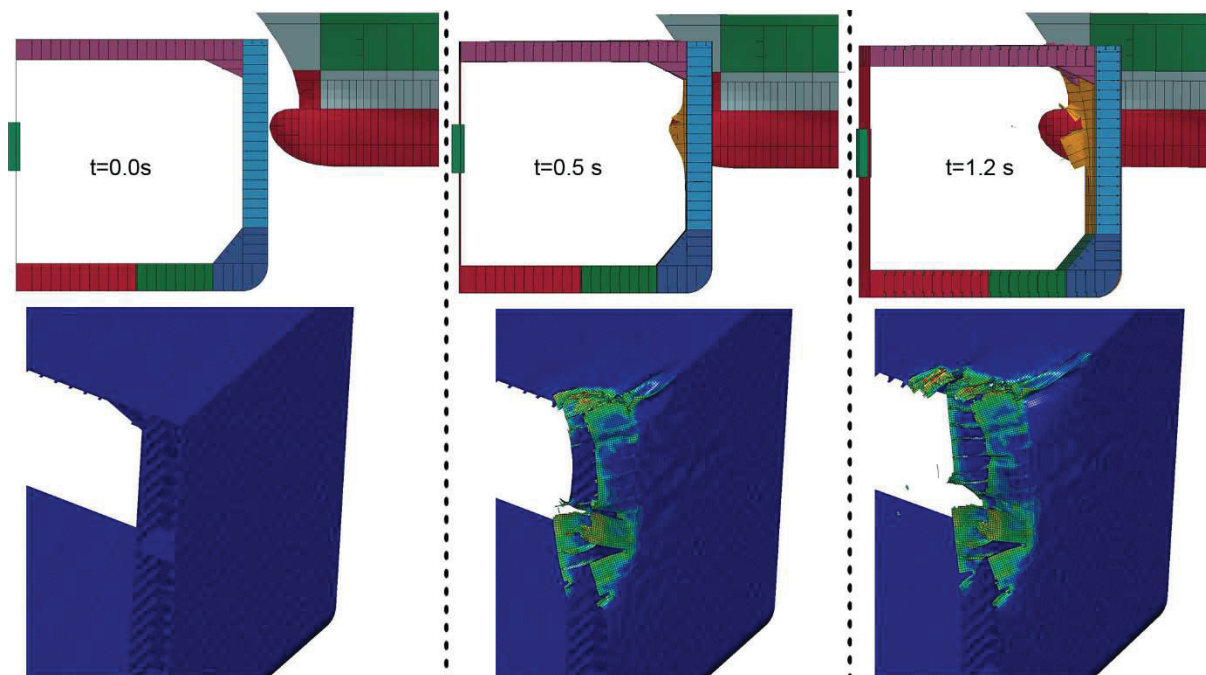


Fig. 6: Progress of collision on one of the tested models

3. Ship crashworthiness surrogate models

In order to prepare surrogate models of struck ship crashworthiness, first it is necessary to select the relevant measures of crashworthiness. Internal energy absorbed by the structure during collision is usually used as a crashworthiness criterion, e.g. *Klanac et al. (2009)*, *Ehlers (2010)*. Usually, maximal internal energy is used, however, for practical purposes, maximal internal energy is substituted with Internal energy absorbed during the first 1.2 s $E_{it=1.2}$.

One of the most important parts in preparation of surrogate models is the selection of relevant control parameters that influences the selected surrogate model responses. Based on the previous work, the relevant parameters that influence the struck ship crashworthiness includes:

- topology parameters like number of web frames, number of side stringers, side stiffener spacing
- geometry parameters like double side width, height of web / breadth of flange of longitudinal and transfer stiffeners
- scantlings like outer shell thickness, inner hull thickness, side stringer thickness, and off course web / flange thickness of longitudinal and transfer stiffeners.

In order to enable simple generation of models that combine all of those parameters, it has been decided to prepare in-house model generator, since it has been estimated that preparation of few hundreds different topology/geometry model combinations would take more time than preparation of an in-house model generator.

The preliminary study presented in this paper includes two control parameters: one geometry parameter (double side width) and one scantling parameter (thickness of the side shell). Both parameters were tested on three levels, Table 2.

Table 2: Preliminary study control parameters

Parameters	Level 1	Level 2	Level 3
Double side width	2000 mm	2100 mm	2200 mm
Side shell thickness	13.5 mm	15.5 mm	17.5 mm

In order to study influence of all effects, including removal of experiments, full factorial design is used, which result with the total of 9 experiments, Table 3. Since full quadratic model for two parameters have 6 unknowns, that requires 6 experiments for their determination, the remaining experiments are used for the evaluation of model error.

3.2. Numerical analysis results

The numerical experiments have been executed on IBM x240 (Xenon E5-2680 v3/ 32GB RAM) using 8 cores for each experiment. Average time for each simulation was 36 hours. Figs. 7 and 8 present time-domain results for C20 and A20 models, respectively. Main results for all the models are listed in Table 3. Fig. 7 presents C20 model energy distribution typical for long-time, i.e. $t=1.9s$ collision simulations. Only models B20 and C20 were subjected to prolonged simulation. Figure 8 presents A20 model energy distribution, typical for short-time, i.e. $t=1.2s$ simulations. Two different run times were chosen for the following reasons. Short-time simulation was chosen to save the cost of the calculation and at the same time to reach the inner hull breach confidently. Long-time simulation was chosen to examine the results after the moment when internal collision energy has reached the maximum.

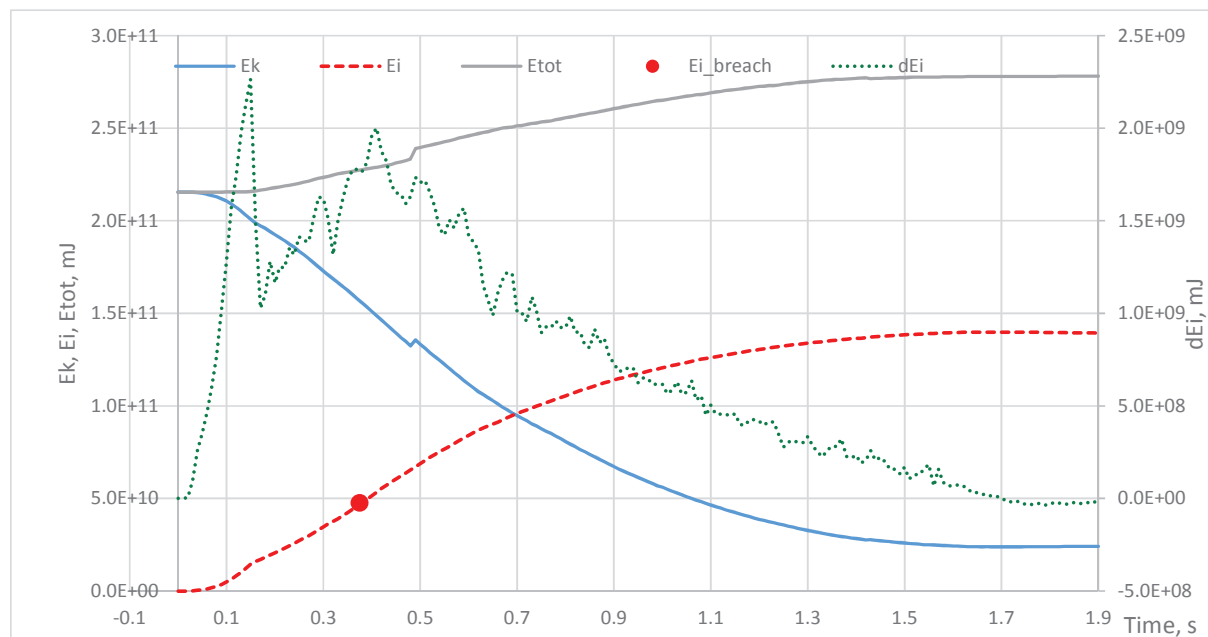


Fig. 7: Model C20 Results

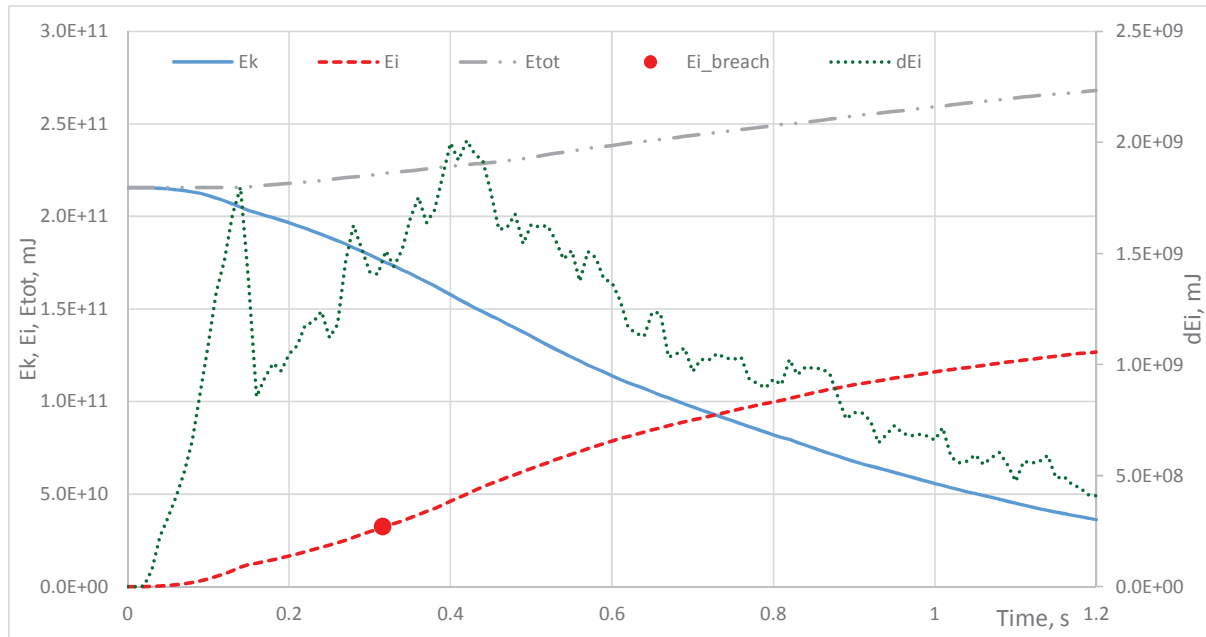


Fig. 8: Model A20 Results

On both Fig. 7 and 8 the following is presented:

- Blue line presents the kinetic energy in the system. As the struck ship is not moving, kinetic energy in the system is generated by the speed and mass of the striking ship, namely a 6889 t ferry with an initial speed of 8 m/s. Once the contact between ships occurs, available kinetic energy is transformed into internal energy, as well as being lost by friction during the contact.
- Red line presents the internal energy, being the energy generated by elastic and plastic deformation of the structure, both for the struck and the striking ship. Each finite element deformation is measured and the related energy is calculated until the critical strain is detected and element erased from further calculation. A sum of internal energy is a measure of damage on both ships.
- Grey line presents the total energy in the system and in the LS-Dyna it is a sum of initial total energy plus the external work, which is in this case mostly the contact energy.
- Finally, green line presents time-step distribution of internal energy, indicating the gradients of internal energy during the collision.

Table 3: Experiment results

Model	t_s, mm	b_s, mm	t_{breach}, s	$E_{i, breach}, mJ$	$E_{i, t=1.2}, mJ$
A20	13.5	2000	0.3158	3.26 E+10	1.267 E+11
B20	15.5	2000	0.3774	4.55 E+10	1.297 E+11
C20	17.5	2000	0.3750	4.77 E+10	1.308 E+11
A21	13.5	2100	0.3922	4.57 E+10	1.245 E+11
B21	15.5	2100	0.3513	4.01 E+10	1.265 E+11
C21	17.5	2100	0.3871	4.76 E+10	1.277 E+11
A22	13.5	2200	0.3807	4.18 E+10	1.253 E+11
B22	15.5	2200	0.4129	5.09 E+10	1.269 E+11
C22	17.5	2200	0.4237	5.50 E+10	1.275 E+11

3.3. Surrogate model of an internal energy

As given above, an internal energy absorbed during the first 1.2 s $E_{it=1.2}$ is used instead the maximal internal energy. Full quadratic response surrogate model have been used as a starting model.

Backward elimination procedure was planned to be used for exclusion of members that have been marked as not significant (F test value greater than 0.1). However, $E_{i, t=1.2}$ response surface model for obtained experiment responses have resulted with full quadratic model, since all model factor, including interaction of control parameters were significant. Final analysis of variance (ANOVA) for this model is given in upper part of Table 5, while the model equation and some basic statistic measures are given in lower part of the table. Adjusted R2 is high and in very good correlation with Predicted R2.

Some of the surrogate model diagnostics plots, Residuals vs Predicted and Predicted vs Actual, are presented in Fig. 9. Fig. 10 shows resulting surrogate model in 3D plot together with the numerical experiments used for the generation (marked with spheres).

Table 5: Surrogate model statistics

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	6.33E+19	5	1.27E+19	800.9	< 0.0001	significant
A-TPL	3.06E+19	1	3.06E+19	1936.5	< 0.0001	
B-Width	1.9E+19	1	1.9E+19	1200.9	< 0.0001	
AB	1.82E+18	1	1.82E+18	115.08	< 0.0001	
A^2	1.37E+18	1	1.37E+18	86.98	< 0.0001	
B^2	1.05E+19	1	1.05E+19	665.07	< 0.0001	
Residual	1.9E+17	3	1.58E+16			
Lack of Fit	1.9E+17	3	6.32E+16			
R ² =0.9970, Adjusted R ² =0.9958, Predicted R ² =0.9936, Adequate Precision=90.24						
E _{i, t=1.2} = 7.426E+11 + 1.034E+10 t _s -6.563E+8 b _s -2.383E+6 t _s b _s -1.465E+8 * t _s ² + 1.620E+5 b _s ²						

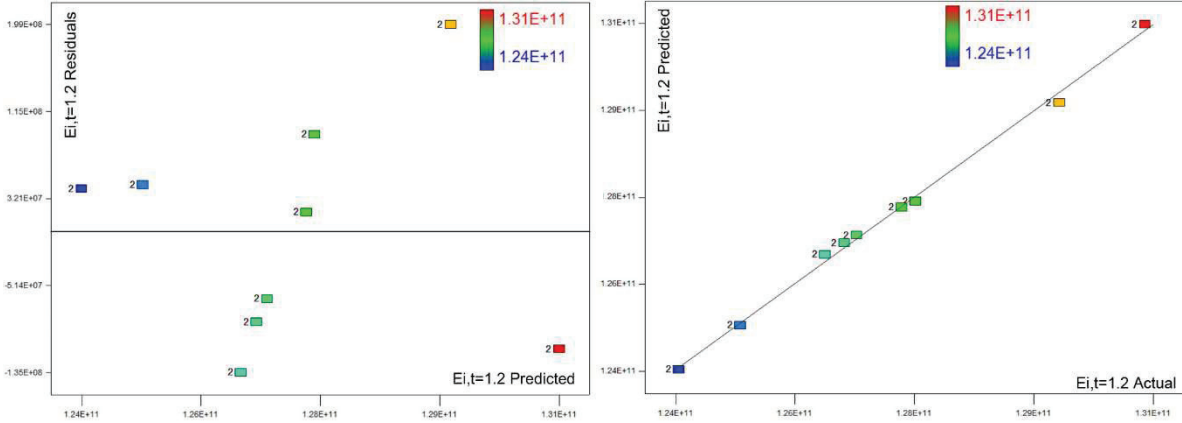


Fig. 9: Surrogate model diagnostic

Based on the presented surrogate model statistics and diagnostic plots, it is reasonable to conclude that the internal energy surrogate model is in a very good agreement with simulation results, and that its usage in optimization is reasonable, of course inside of used control parameters interval. However, as indicated above, those are just preliminary results on two control parameters. The study continues with inclusion of other relevant control parameters, and it is expected that the complete study will be finished by the end of 2016. Also, the further study will include modelling of other possible crashworthiness measures that sounds reasonable (e.g. internal energy absorbed until the inner hull breach, size of the hull rupture after collision, etc.). The first step will be to extend simulation time to at least 2 second in order to catch maximal internal energy.

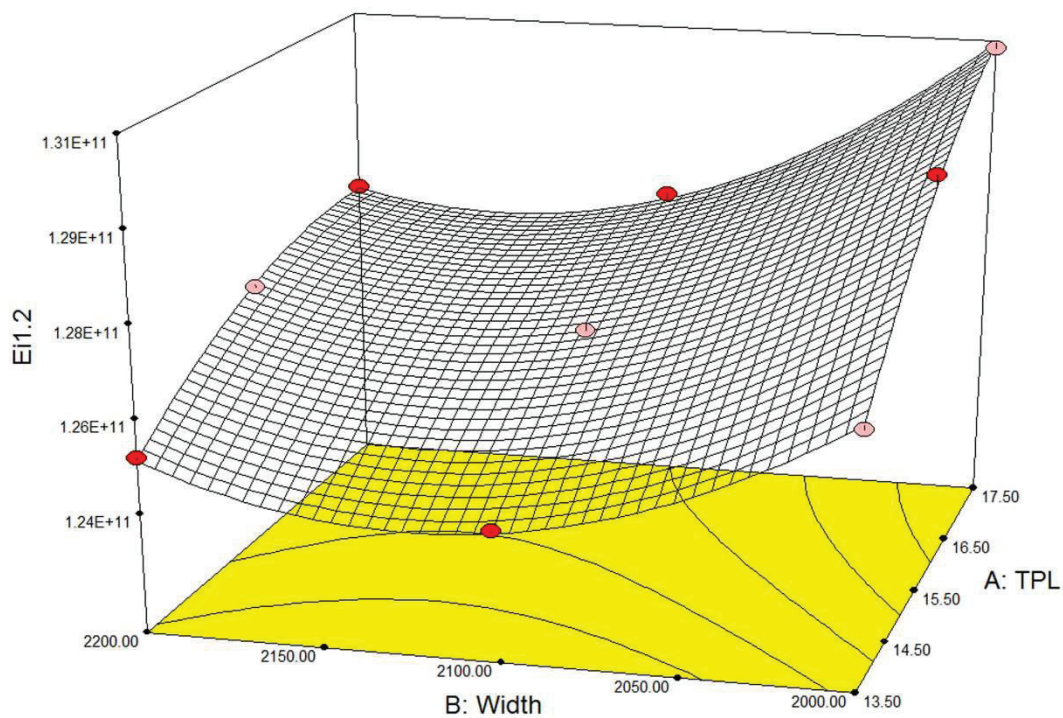


Fig. 10: Surrogate model 3D plot

4. Conclusions

The design of a ship structure falls within the category of large scale problems characterized by several design objectives, hundreds of design variables and tens of thousands of design constraints. The objective of the research partially presented in this paper is to evaluate ship crashworthiness surrogate modelling possibilities in order to evaluate suitability of their usage in the improved tanker structural design process. The preliminary results presented here show that the accuracy of an internal energy surrogate model with respect to the used control parameters is more than adequate for use in optimization. This is a very good motivation for the continuation of research and preparation and evaluation of surrogate model that will include all other relevant control parameters.

Acknowledgment

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