Steel structures optimization to resist underwater shockwaves - explosive charges optimization

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Abstract

Steel structures are largely used in critical applications – such as in aerospace, marine and oil industries. Failure of these structures can often be catastrophic and the resulting damages can be not only very costly, but irreversible to the environment. Shockwaves produced by underwater explosions can cause these effects over offshore platforms, ships, and dams, with the imaginable devastating results.

Underwater explosions can be accidental or intentional. Powerful explosives and even armament are currently available in the black market to anyone willing to spend the right amount of money. There is, therefore, a need to better understand the dynamic response of such structures when subjected to shockwaves caused by underwater explosions, so that this knowledge can be applied in future designs or even to introduce modifications on existing ones in order to increase their survivability.

A method for structural optimization – focused on their dynamic response to underwater explosions, combining Genetic Algorithms and Finite Elements is being developed. As part of this development, due its complementary aspect, a study to optimize explosive charges focusing their effects on submerged steel structures is being conducted. In this work, this study is outlined and some numerical solutions are presented.

1 Introduction

The terminal effects of underwater explosions on steel structures are dependent on factors such as explosive charge mass, relative position and distance from
explosion to target, and depth, among others. These effects can be calculated by numerical simulation, e.g., Finite Elements (FE). The result will depend on the model complexity, but, on the other hand, as the model complexity grows, also grows the computational effort.

The use of Genetic Algorithms (GA) allows the use of very simple and robust codes to search global points of maximum (or minimum) of any function, despite its local variations (admitting that the function has a point of maximum – or minimum, in the considered domain). This is possible due to the intrinsic evolutionary characteristics of GA, which are well described in Goldberg [1]. In GA, sets of individuals constitute generations, and all individuals in a generation have a measure of fitness to some function, which indicates their ability for potential success in a given situation. These values of fitness are used to rank them, so that the individuals with low values of fitness will tend to be replaced by new individuals in the following generation.

Thus, it is possible to assemble a fitness function for a configuration. Resulting stresses, displacements, and deformation, among others, can be the input data for this function. This input data will be dependent on structural (e.g., material properties and design geometry) and load parameters (e.g., explosive charge mass and its relative position to the structure), which can be calculated through simulation using FE. The simulation for each possible configuration, therefore, provides values that may be combined with other parameters and be used to calculate a value of fitness for that configuration.

Several experiments need to be carried on some well-defined structures models with various load configurations (explosive charge mass and distance from explosion), in order to better understand their response to such impulsive loads. The objective of this study is to optimize a TNT charge considering the effects of its detonation over the selected structure, its cost, and other parameters, described ahead.

It must be observed that the data presented in this work is not actual data. Classified information has been replaced and fitness functions have been specially created for publication purposes.

2 Development

2.1 Model problem

The model problem herein presented consists of a simple 2D cylindrical steel structure submerged in water. The fluid-structure interaction was neglected, and added mass was adopted to take the fluid mass into account. The main problem parameters are as follows:
- material = structural steel
- diameter = 6.0 m
- equivalent hull thickness = 0.10 m
- equivalent deck thickness = 0.10 m
- heavy-weight equipment mass per length unit = 2,000 Kg/m
- TNT mass range: from 80 – 160 Kg
- explosion distance range: 10 – 20m
- number of elements in hull: 80
- number of elements in deck: 24

A mixed rubber-steel element was selected to represent the deck support on the hull. A sketch of the model is shown in figure 1.

Figure 2: Sketch of the model problem.

The relevant points in figure 1 are the nodes “North” (N), “South” (S), “East” (E), and “connect 1” (C1) – connecting the hull and the deck. These points are relevant due to geometric symmetry (N, S, and E) and stress concentration (C1).

The source of the explosion was assumed to be in the same depth of the center of the structure, 20 m, as shown in figure 2 (this is important because the resulting underwater shockwave is depth dependent):

Underwater shock damage is measured by the peak vertical velocity (for surfaced ships) and by the peak translational velocity (for submerged submarines) rather than by the water overpressures produced by the shock front. Underwater shock produces rapid accelerations that can disarrange equipment and machinery, rupture hulls, and/or injure personnel. Both the directly transmitted shockwave and the shockwave reflected from the sea bottom can be damaging. The shock wave initially travels several times the speed of sound in the water but quickly slows down to hypersonic speed. More complete information about Underwater Shockwaves can be obtained in Motta et al [2] and Cole [3]. Therefore, the load amplitude and energy by themselves do not allow predict the level of damage that an explosion might impose to the structure.

The adopted approximation for the underwater shockwave shape is an impulse with exponential decay, such as presented by Geers [4]. Assuming that the explosion source is punctual, the wave propagates spherically, and its amplitude decays with distance, as shown in Figure 3 for 160 Kg of TNT.
2.2 Numerical solution

The method for the numerical solution of the problem was presented by Motta et al [5]. It is based on a family of ODE solvers developed by Brown et al [6], [7], VODPK. This code combines implicit integration rules of variable order to integrate initial value problems (IVP), preconditioning, and a matrix-free Krylov solver. Plane strain state is assumed. Bilinear isotropic kinematic hardening material with viscous-plastic behavior is modeled. Geometric nonlinearity and large deformations are allowed to occur.

Due to the impulsive characteristic of the load, the structural response decays rapidly to unimportant ranges, so that all relevant information happens in the
initial 10 milliseconds. This is important because it is necessary to calculate the solution for \( n \) individuals in \( m \) generations (in this study, 100 generations of 100 individuals were used), and the longer the simulation time, the higher the computational effort needed.

### 2.3 Codification

Binary codification was selected. It is simple, efficient, and the GA operations are easy to implement. Since the code has been written in double precision, each individual gene had 128 binary chromosomes, the first 64 representing the TNT mass (\( \text{wtnt} \)) and the others 64 the distance (\( d \)) from the TNT charge to the hull. This codification followed the IEEE754 standard [8].

### 2.4 The fitness function

The value for fitness in this problem was obtained by the following combination of the various values obtained from the functions shown in figure 4:

\[
f(\text{wtnt}, d) = \left( f_I + \frac{f_{II} + f_{III} + f_{IV} + f_{V} + f_{VI}}{5} \right)/2
\]  

(1)

Figure 4: Fitness functions for: (I): TNT mass; (II): distance; (III) person acceleration; (IV) light-weight equipment acceleration; (V) heavy-weight equipment acceleration; and (VI) maximum stress / yield stress ratio.
The subscript indicates the corresponding chart in figure 4. As they show, fitness values were given according to the mass of TNT (representing the cost - I), the distance from the explosion to the nearest hull point (II), acceleration imposed to a person standing in the deck (III), acceleration imposed to the fixation point of shock absorbers of light-weight and sensitive equipment (IV), acceleration imposed to the supporting point of shock absorbers of heavy-weight equipment (IV), and the ratio between the maximum stress in the hull and the yield stress for the material (VI). Since the first function is the only one with negative slope, it received a bigger weight in the total fitness function for demonstration reasons. The values from functions III, IV, V, and VI depend on the simulation.

2.5 Simulation environment

The simulation environment was the cluster Mercury from UFRJ. It has 16 dual-Pentium III 1.0GHz nodes and processing times for various numbers of processors are shown ahead.

Further information on this cluster is available at www.nacad.ufrj.br.

3 Experimental results

Equivalent stress values for the relevant points in figure 1 for a 160 Kg TNT charge at 10 m from the model are shown in figure 5 for 10. It can be noticed that the stresses nearly pass the yield stress. The normal stress x normal strain curves for the same points and time are shown in figure 6.

Figure 5: Equivalent stresses at relevant points.

Figure 6: Stress x strain curves at relevant points.
The optimization for this demonstration problem data and results are shown in tables 1 and 2, respectively. Again, the physical data for this problem were given in section 2.1.

<table>
<thead>
<tr>
<th>Table 1:</th>
<th>Demonstration problem data.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>100</td>
</tr>
<tr>
<td>Generations</td>
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<tr>
<td>Elitism</td>
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</tr>
<tr>
<td>Crossover probability</td>
<td>30%</td>
</tr>
<tr>
<td>Mutation probability</td>
<td>5%</td>
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<thead>
<tr>
<th>Table 2:</th>
<th>Optimization results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best suited individual</td>
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</tr>
<tr>
<td>TNT mass (Kg)</td>
<td>159.965410</td>
</tr>
<tr>
<td>distance (m)</td>
<td>10.003914</td>
</tr>
<tr>
<td>fitness</td>
<td>84.790305</td>
</tr>
</tbody>
</table>

The required time to complete the optimization process is shown in figure 7 for 1, 5, 10, and 20 processors (measure using Fortran function \texttt{cputime()}).

![Figure 7: Required times for optimization with 1, 5, 10, and 20 processors](image)

From figure 7, it can be observed that the communication overhead as the number of processors changes from 1 through 20 is nearly none.

4 Conclusions

A new method for steel structures optimization combining GA and FE is being developed. As part of this development, a study to better understand submerged structures dynamic response to shockwaves produced by underwater explosions is being conducted. In this study, TNT charges are being optimized, according to the effects their resulting shockwaves, when detonated, produce on certain fixed structures. The development environment is a PC cluster, with distributed memory.

In this work, this study was outlined and some results were presented, showing that the method has a great potential. Further development is necessary to produce more information.
References


