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Theoretical description of the design of naval structures subjected to dynamic loads: a critical review considering the finite element analysis of exposed decks subjected to the shock wave pressures generated by gunfire (Gun Blast)

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Abstract

The structural analysis of exposed decks on military vessels under dynamic loads induced by gun firing represents a challenge of growing relevance in modern naval engineering. Standard NES 154, which for decades has been the de facto reference for the design of weapon-supporting structures, proposes replacing and simplifying the dynamic load caused by the gun blast with a static pressure equivalent to 25% of the gun blast's peak value. This reduction, while operationally practical, it omits critical variables that determine the actual structural behavior: pressure variation over time, fluid-structure coupling, and inertia effects inherent to the transient dynamic regime. This systematic review aims to examine, based on recent literature (2020-2025), the theoretical foundations of design of naval structures under dynamic loads, shock-wave propagation models in free space and over structural surfaces, finite element methods (FEM) applied to nonlinear transient state, and the analysis alternatives to the static simplification specified in NES 154. Methodological gaps have been identified that justify the need to apply transient dynamic analysis using a linear elastic model with small deformations—which can be implemented in platforms such as ANSYS—for the rigorous evaluation of the exposed deck of military ships, such as the Offshore Patrol Vessels (hereinafter OPV-type vessels), equipped with the Oto Melara 76 mm gun. The findings converge on the conclusion that the difference between the safety factors obtained through static approximation (recommended by NES 154) and those derived from dynamic analysis can be significant, with has direct implications for the structural integrity and reliability of military ships.

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1. Introduction

The continuous increase in the deterrence capacity of contemporary military fleets has led to the integration of larger caliber weapons systems in OPV-type patrol boats. In the specific case of the National Navy of the Republic of Colombia (hereinafter ARC), the change from the 40 mm single-tube cannon installed on the first unit (OPV I) to the 76 mm Oto Melara cannon used by the third unit (OPV III) clearly accounts for this increase. This increase is decisive from the structural point of view: the 76mm gun establishes at the time of firing charges of dynamic origin that are essentially more complex than those generated by smaller calibers, both in magnitude and in their temporal profile. Historically, the design of under- and above-deck structures supporting naval armament has been supported by the Naval Engineering Standard NES 154 (1989, revised 2000), which in its numeral 4.5 allows the dynamic load produced by firing to be transformed into an equivalent static pressure, preset at 25% of the maximum peak pressure generated by the gun blast. This simplified approach has been a consequence of the need to be able to provide calculation procedures in the field of computer systems for the resolution of calculation problems when such means were quite limited (NES 154 is from 1989). However, in the simplification process, the temporal evolution of the load, the fluid-structure coupling phenomenon and the inertial response of the structural mass are lost sight of, aspects that determine the real behavior of the roof at the time of each shot and after it (Trajkovski et al., 2020; Goel et al., 2021).

The growth of finite element methods (FEM) and the existence of simulation platforms such as ANSYS have radically changed the possibilities of structural analysis in naval design. Nowadays it is possible to solve the transient dynamic analysis in elastic linear regime and small deformations under the influence of full load obtained from the shock wave, with a level of detail impossible to obtain from the static analysis approximation allowed in the NES 154. the most recent studies show that the differences between the two approaches—in Von Mises stress, total deformation, or the safety factor—are relevant, with direct implications for the structural integrity of the vessel (Costa & Lagasco, 2022; Rajendran et al., 2023).

In this sense, this systematic review seeks to consolidate the recent state of the art (2020-2025) of scientific research in four interrelated axes over time: (i) theoretical foundations of the resistance of materials on dynamic shock and impact loads; (ii) physical-mathematical models of a shock wave from the firing of a cannon; (iii) FEM modeling methods and strategies for the transient analysis of naval structures; and (iv) technical limitations of the simplification set out in NES 154 (1989) compared to the dynamic methods available today. The review will have a critical interpretative vision, aimed at substantiating and contextualizing the finite element analysis of the exposed deck of military ships, such as those of the OPV type, subjected to the inevitable dynamic loads produced by the 76 mm Oto Melara cannon in each of its shots.

2. Review Methodology

The bibliographic search was carried out in the Scopus, Web of Science, ScienceDirect and Google Scholar databases, using the following descriptors: "gun blast", "muzzle blast", "shock wave naval structure", "finite element transient dynamic naval", "fluid-structure interaction blast", "NES 154 dynamic load", "Von Mises stress naval deck", "OPV structural analysis" and "Oto Melara 76 mm". The Boolean operators AND and OR were used with the idea of combining terms, limiting the results to the periods between January 2020 and December 2025, in order to ensure the timeliness and relevance of the literature in question.

Original research articles, systematic reviews and technical reports that had been published in journals indexed in Q1 to Q3 quartiles, current international technical standards and doctoral theses from institutions with outstanding experience in naval engineering and applied mechanics were included. Papers without peer review, general dissemination materials, and publications prior to 2020 were excluded, except for seminal references whose deletion would have compromised the historical coherence of the theoretical framework. The selection process resulted in a corpus with 42 valid references that were classified thematically based on the axes of analysis indicated in the introduction.

3. Theoretical Foundations Of The Resistance Of Materials To Dynamic Loads

3.1. Nature of dynamic impact and shock loads

The difference between the type of static load you started working with and the type of dynamic load you will work with next is not based on the magnitude of the load that will be applied here, but on the speed of the load. Therefore, it also has to do with the representation that originates in the inertial response that the structure obtains. In loads where the duration is on the order of the natural period of vibration of the structural system or lower, it is evident that the inertia effects and damping forces determine the mechanical behavior of the system (Chopra, 2020; Clough/Penzien, 2020). In the case of firing a 76 mm gun, the contact time of the shock wave with the casing is on the order of milliseconds, as can be deduced from the representation of the type of dynamic charge that has to do with high-rate shock or impact charges. A structure subjected to shock loads can be described from the general equation of motion from the perspective of solid mechanics:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\}$$

where the matrices [M], [C], and [K] are the mass, damping, and rigidity of the system, respectively; the vectors $\{u\}$, $\{\dot{u}\}$ and $\{\ddot{u}\}$ are the nodal displacements, velocities and accelerations; and the vector $\{F(t)\}$ corresponds to time-dependent external forces. In transient dynamic analysis, the above equation is obtained by numerically integrating into the time domain using methods such as the Newmark or Hilber-Hughes-Taylor (HHT) methods, which ensure the stability and accuracy of the solution for sufficiently small time steps (Bathe, 2022; Kwon & Bang, 2021). The fundamental difference compared to static analytics is that, without considering the terms of inertia $[M]\{\ddot{u}\}$ and damping $[C]\{\dot{u}\}$, the possibility of evaluating the effect of time on the structural response is lost. This loss is valid for the case in which the charge changes slowly enough to be able to speak of the fundamental period of the structure, but not for the case of gun blast charges, where the positive charge phase can be completed in times close to $T+ = 5\text{-}30$ ms (Kingery and Bulmash, 2021; Remennikov, 2023). In this case, the real response of the structure may be much greater than that predicted by the equivalent static analysis or oscillations and superposition of effects that are not definitive without being able to clear the temporality of the displacement field.

3.2. Elastic behaviour and failure criterion in naval steels.

Ship-type high-strength structural steels (AH36, DH36, EH36), materials that are often used in the construction of OPV type vessels, exhibit a purely linear elastic behavior for small deformations, ranges within which the behavior of the material is governed by the generalized Hooke's law; the elastic linear regime hypothesis is fulfilled if the stresses caused in the part do not exceed the yield limit of the material, which gives continuity to the methodology set out in the analysis carried out in this work (Lehmann, 2021; Paik, 2020). The von Mises criterion, known as the distortion energy criterion, is considered the most widely used to establish the onset of creep in isotropic ductile materials that are subjected to a multiaxial stress state. The equivalent von Mises effort can be calculated using the following mathematical relationship:
$\sigma_{VM} = \sqrt{[(1/2)\cdot((\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2)]}$ σ_1, σ_2 and σ_3 are the main stresses of the stress state. The creep condition is established when $\sigma_{VM} = \sigma_y$, with σ_y being the yield limit of the material. In transient dynamic analysis, the σ_{VM} field varies over time and it is necessary to determine not only the maximum value but also the distribution in space and duration of the nodes or elements subjected to certain increases in these limits (Abramowicz, 2020; Paik, 2020); These aspects are fundamental for the structural improvement to be proposed.

The strain rate has a known effect on the dynamic yield limit of naval steels: by increasing the rate of application of the load, the material effectively exhibits a higher strength than that obtained in static or normal type tests; this effect is strain rate hardening, a behavior that can be modeled in the case of naval steel according to the Cowper-Symonds equation, but which, in the case of gun blast charges with small deformations, turns out to be a minor correction, such that it does not alter the framework of an elastic linear analysis (Trajkovski et al., 2020; Goel et al., 2021).

4. Physics Of The Shock Wave Produced By The Firing Of A Cannon

4.1. Gun blast generation and propagation

When the projectile is fired from the muzzle, the combustion gases at high pressure and temperature expand violently into the atmosphere. As a result of this expansion, a pressure disturbance is caused that is called a muzzle shock wave or gun blast. This wave propagates radially from the muzzle of the weapon at supersonic speeds, and its interaction with any structural surface in its path gives rise to a phenomenon of reflection and diffraction and transmission that will determine the effective local charge at each of the points of the deck (Anderson, 2021; Dobratz & Crawford, 2021).

The time profile of pressure at a fixed point in space has the shape described by the modified Friedlander equation with great precision. After an almost instantaneous increase to the peak of overpressure P_s^+ at the instant t_a the wave arrives, the pressure decreases exponentially during the positive phase, which is of duration T^+; subsequently, the pressure is reduced below atmospheric pressure, in the negative phase and duration T^- (Chaurasia et al., 2021; Kingery & Bulmash, 2021):
$p(t) = p_0 + P_s^+ \cdot (1 - t/T^+) \cdot e^{(-b\cdot t/T^+)}$
p_0 is the reference atmospheric pressure and b is the empirical decay parameter that controls the shape of the positive phase. T^+, P_s^+ and b are determined by the energy of the explosive, the distance to the observation point, the angle of incidence and the local atmospheric conditions. Its experimental or empirical determination is a prerequisite for any somewhat serious transitional analysis (Remennikov, 2023; Shi et al., 2022).

4.2. Spatial distribution of pressure on the roof

The distribution of pressure on a flat surface—such as the horizontal surface of an exposed deck of a ship—is not homogeneous: it decreases as the point of normal incidence is radially away, and it also varies as the angle of elevation of the gun changes. Costa and Lagasco (2022) propose a three-dimensional model that assigns the pressure at each of the points of the roof to its position in the calculation plane using measurable geometric parameters: the height of the muzzle above the roof (h), the horizontal radial distance to the reference point (r) and the azimuth angle (θ). This model, which extends the two-dimensional approach of previous work, allows the calculation of the pressure field that will be required as a boundary condition of the transient dynamic analysis in FEM.

More recent studies have introduced computational fluid dynamics (CFD) methods to obtain the pressure field more closely to the physical representation of this phenomenon, although at a significant computational cost (Nguyen et al., 2024; Shin et al., 2023). Although Costa and Lagasco's (2022) model is an analytical approach, it is considered sufficiently relevant in the context of this work since the task sought is the transient structural analysis and not the detailed characterization of the aeroacoustic field of the shot.

4.3. Scale parameters and empirical models for naval guns

The prediction of the values of the parameters corresponding to the gun blast is normally based on empirical scale laws deduced from explosives tests. The Hopkinson-Cranz scale or cubic similarity law expresses that the properties of the shock wave are a function of the scaled distance Z = R / W^(1/3), where R is the distance from the explosion center and W the equivalent mass of TNT (Dobratz & Crawford, 2021; Leppänen, 2022). The direct application of a conventional cannon to the gun blast needs to be treated with caution, since the geometry of the event—emergent wave from the tube with hot gases and a moving projectile—is remarkably distant from the detonation in the free field (Fansler et al., 2021; Heaps et al., 2022).

For the 76 mm Oto Melara gun, the gun blast is offered by the manufacturer in the form of tables or curves that relate distance, angle of incidence and values of P_s^{+} and T^{+}. This information, reserved for operational use, is the key input for transient analysis and largely determines the quality of the structural response obtained (Washsberger et al., 2020; Rajendran et al., 2023).

5. TRANSIENT DYNAMIC FINITE ELEMENT ANALYSIS IN NAVAL STRUCTURES

5.1. Problem formulation and boundary conditions

The finite element method (FEM) is the most widely accepted computational tool among the engineering community studying modern ship structures, and the application of FEM to transient dynamics already exists firmly in the scientific literature (Hughes, 2022; Bathe, 2022; Zienkiewicz et al., 2022). In the study of the exposed cover and the application of the gun blast, the problem statement is formed by three interconnected components: the geometric discretization of the structure, the formulation of the mechanical boundary conditions, and the load history represented as the function p(t) evaluated in each of the nodes of the exposed surface. Discretization is usually done with four-node shell elements, which present an adequate compromise between accuracy and computational cost for sheet metal structures with moderate slenderness, which can be that of the panels and reinforcements of the roof of an OPV (Paik, 2020; Lehmann, 2021). Mesh density must satisfy convergence criteria that have been systematically studied for blast problems by Trajkovski et al. (2020), who propose the MMALE method with minimal mesh design criteria that avoid underestimation of peak pressure in cells closest to the source.

The boundary conditions reflect the type of junction between the deck and the vertical bulkheads, the keel and the rest of the ship's structure. In practice, they are modelled using displacement constraints or equivalent spring stiffness that reproduce the behaviour of the surrounding structural assembly without the need to model the entire vessel (Shin et al., 2023; Li et al., 2024). The choice of these conditions has a significant influence on the distribution of maximum stresses and, therefore, on the location of the critical points that would motivate eventual structural improvements.

5.2. Temporal integration and numerical stability

The integration of the equation of motion in time can be done by implicit or explicit methods. Implicit methods—such as the Newmark-β algorithm or HHT-α available in ANSYS Mechanical—are unconditionally stable for certain parameter ranges and allow for relatively large time steps, making them particularly suitable for moderate-duration problems with low-frequency response (Kwon & Bang, 2021; Bathe, 2022). Explicit methods, on the other hand, are conditionally stable and require time steps on the order of the wave's transit time through the smallest element of the mesh (CFL criterion), but they are superior for high-speed and very short-duration problems, such as the detonation of explosive charges (Nguyen et al., 2024; Leppänen, 2022).

For the gun blast of a 76 mm gun, whose positive phase lasts on the order of 10-30 ms and whose relevant structural effect extends several cycles of natural vibration of the cover, the implicit method is generally preferable, as it allows both the rapid loading phase and the post-firing structural recovery phase to be efficiently resolved (Rajendran et al., 2023; Costa & Lagasco, 2022). The selection of the appropriate time step should be supported by a sensitivity analysis that verifies the convergence of the results in terms of peak displacement and peak von Mises effort.

5.3. Fluid-structure coupling in gun blast analysis

The phenomenon of fluid-structure interaction (FSI) describes the mutual influence between the shock wave pressure field and the displacements of the structural surface: as the shell deforms, the pressure field changes, and this modification feeds back into the structural response. By means of the equivalent static analysis of NES 154, this coupling is totally disregarded, in terms of the load it is considered as a constant pressure independent of the deformation of the structure (Washsberger et al., 2020).

In more complex dynamical approaches, such as those that model the FSI by jointly solving – or iterative – the equations of fluid mechanics and solid mechanics in coupled domains. This approach could be implemented in platforms such as ANSYS Fluent coupled to ANSYS Mechanical, it is very demanding from a computational point of view but provides results of greater physical fidelity, especially when the deformations of the structure are large enough to disturb the pressure field (Nguyen et al., 2024; Shin et al., 2023; Li et al., 2024). In the case of military ships, such as those of the OPV type, where deformations are expected to be small within the elastic regime, the influence of full FSI on the results is presumably moderate, although not negligible for verification purposes.

5.4. Structural Recovery and Shot Overlap

A dimension of the problem that is often underestimated in static analyses is the recovery phase of the structure after firing. Understood as the time that elapses from the cessation of the charge until the oscillations of the structure are attenuated below a functional threshold, this phase determines whether there is overlap of effects between consecutive shots at a high rate of fire. For the 76 mm Oto Melara gun, whose rate of fire can reach 120 rounds per minute, the interval between shots is 0.5 s, which could be insufficient for complete dissipation of vibration energy in cases of reduced structural damping (Fansler et al., 2021; Rajendran et al., 2023).

The possibility of overlapping loads is especially relevant in low-frequency fatigue stresses accumulated in areas of stress concentration, such as welds between the roof plate and the longitudinal or transverse reinforcements. Recent authors have pointed out that this mechanism can be decisive in the useful life of the structure under real tactical operation, particularly when the design analysis has been based exclusively on the load of a single shot (Goel et al., 2021; Shi et al., 2022; Abramowicz, 2020).

6. LIMITATIONS OF THE STATIC SIMPLIFICATION OF THE NES 154 STANDARD

6.1. Scope and regulatory context

The British Ministry of Defence's military naval engineering standard NES 154 has been the paradigm for the structural design of the decks on which naval armament is transited for more than thirty years. Its numeral 4.5 establishes that the firing charge can be represented as a static uniform pressure that is equivalent to 25% of the peak pressure of the gun blast, which is distributed over the area of the panel between reinforcements. This specification has the virtue of its simplicity and universality, although it is based on conservative hypotheses that are adopted as a lack of practical alternative methods, not as a physical characterization of the phenomenon (Paik, 2020; Lehmann, 2021).

It should be noted that the rule itself recognizes the simplistic nature of the procedure and does not present it as the correct representation of the dynamic response of the structure. But in practice, the lack of alternative prescriptions of similar accessibility has led to their widespread application in those projects that, such as the "ARC Boyacá", use weapons systems of greater caliber and high rate of fire than those considered when the standard was developed (Washsberger et al., 2020; Rajendran et al, 2023).

6.2. Omitted variables and consequences on the safety factor

The transformation of the dynamic charge to an equivalent static pressure entails the loss of information of four first-order physical properties. Firstly, the value of the time interval during the evolution of pressure: the p(t) function of the gun blast is not a constant value, but is a sign that presents a very marked peak followed by an exponential decay, in such a way that the energy that is transferred to the structure depends on the contact time, as well as the shape of the curve, and not only the peak value (Chaurasia et al., 2021; Kingery & Bulmash, 2021). Second, the way the pressure is distributed over the deck is important. The wavefront does not generate uniform pressure, but produces considerable gradients between the point of greatest impact and the peripheral areas (Costa and Lagasco, 2022).

Third, the inertia and damping effects that affect the dynamic response of the structure must be considered. The natural frequency of the deck panels and their interaction with the excitation frequency of the weapon blast determines whether the structure undergoes dynamic amplification, resulting in stresses that exceed the values predicted in a static analysis, or if, on the contrary, attenuation occurs. This phenomenon, known as dynamic amplification factor (DAF), can exceed unity in certain geometric and material configurations, which calls into question the premise of conservatism present in the NES 154 standard (Goel et al., 2021; Shin et al., 2023).

A fourth aspect to consider is the effect of overlapping successive shots, as mentioned in the previous section.

Recent comparative research has evaluated the differences between the safety factor derived from the NES 154 approach and that obtained by transient dynamic analysis in structures similar to those of military ships, such as those of the OPV type. The findings indicate that dynamic analysis can identify critical areas that are not detected by the static method, revealing local overstresses that can reach 20-40% more than anticipated in certain reinforcements (Trajkovski et al., 2020; Rajendran et al., 2023; Li et al., 2024). This methodological discrepancy is not insignificant and has a direct impact on the structural safety of the vessel in real tactical operational situations.

6.3. Proposals for improvement and alternative frameworks

Based on the aforementioned limitations, recent literature presents different methodological strategies that allow preserving the practicality of the design without losing the physical rigor of the analysis. One of them corresponds to the use of tabulated dynamic amplification factors, which derive from parametric analyses of the response of OPV-type vessel panels for gun blast loads, and which could be used as a correction of the NES 154 procedure (Leppänen, 2022; Remennikov, 2023); a second, more faithful alternative would be the implementation of elastic linear transient dynamic analysis directly in commercial FEM platforms, considering the load history as a time boundary condition.

In addition, some authors are committed to updating existing naval regulations in order to include procedures for dynamic-standardized analysis, as they have already proposed in other areas of structural engineering subjected to explosion loads, such as the design of terrorism-resistant structures (Paik, 2020; Shi et al., 2022; Abramowicz, 2020) or the development of advanced seismic design. Although this regulatory update exceeds the scope of the project in which the research has been developed; but it has been fully justified due to the bibliographic evidence addressed.

7. Discussion

The systematic review carried out allows us to counteract an argument consisting of the defense of transient dynamic analysis, as a reference for the design and verification of the exposed deck of military ships, such as those of the OPV type. There are three cross-sectional findings that corroborate this statement, the first, the coincidence of a large number of sources in considering that the simplification of the NES 154 does not ensure conservative universality: depending on the temporal relationship between the duration of the positive phase of the gun blast and the fundamental period of the roof panels, the dynamic amplification factor may be greater than unity, so the safety factor calculated under static methods would be equally invalid (Goel et al., 2021, Trajkovski et al., 2020).

The second finding is the technological maturity of the computational tools that are available to implement transient dynamic analysis. In its latest versions, ANSYS has explicit and implicit transient analysis modules that are applicable to the problem itself, with the ability to include the complete history of gun blast loading, proportional structural damping (Rayleigh model), as well as boundary conditions relevant to the roof structure. The literature presents examples of the implementation of these tools with respect to problems structurally equivalent to those of military ships, such as those of the OPV type, (Bathe, 2022; Kwon & Bang, 2021; Nguyen et al., 2024).

The third finding is of an operational nature: that is, that the transition from OPV II to OPV III of the ARC, characterized by the increase in caliber and rate of fire, is not a progressive change, but implies a qualitative leap in structural requirements; the extrapolation of design methodologies designed for calibers lower than the structural requirements of a higher category armament – without being contrasted through dynamic analyses – entails simplifications and assumptions that the current technical literature considers unacceptable (Rajendran et al., 2023; Costa & Lagasco, 2022).

However, in relation to the knowledge gaps seen in the review, it is concluded that the interaction between the gun blast and the structures of military vessels of the OPV type of Latin American manufacture is not specifically contemplated in the recent international literature; The present research project on military ships of the OPV type collaborates in covering this point, and may lead to results that can be transferred to other units in the region that use similar weapons systems.

8. Conclusions

The bibliographic review presented allows us to deduce the main conclusions that can be established. First, the theoretical foundations of the resistance of materials to dynamic shock loads The use of gun blast cannot be characterized without taking into account the marked temporal variability of the blast, the inertial effects of the system itself and the damping.

The equation that determines the dynamics of structures served in the system with its three respective constituent terms is the irreducible framework of the analysis, and its resolution of the problem by means of FEM in the time domain is the methodologically correct approximation. Secondly, the simplification established in the NES 154 standard – static pressure equivalent to 25% of the peak pressure of the gun blast – which, although it has a historical and operational meaning, also obviates all the physical factors that would allow an assessment that would not be complete or conservative of the safety factor that is established, in particular for high-caliber and high-rate of fire reinforcement systems such as those using the Oto Melara 76 mm operating room.

Third, the shock wave models available in the literature —modified Friedlander equation, three-dimensional model Costa and Lagasco (2022)— allow calculating the pressure field on the deck of military ships with a sufficient degree of approximation to be considered for the temporal boundary condition of the transient FEM analysis.

Fourth, modern FEM platforms such as ANSYS contain sufficient algorithms to solve the proposed elastic linear transient dynamic analysis, with robust and proven temporal integration methods. The specialized terminology itself reports direct and analogous applications that offer arguments that support the methodological feasibility of the approach.

Finally, the set of evidence reviewed favors the development of the transient dynamic analysis of the exposed deck of military ships as a methodologically superior alternative to the static approach of the NES 154 standard, with the possibility of identifying critical points that, otherwise, could not be detected by the normative method and also the possibility of structural improvements based on the behavior of the structure under combat operational loads.

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