

Review on Performance Assessment of Slender Steel Frameworks Exposed To Explosive Forces

Vijendra S. Nikam¹, Snehal S. Pawar², Dr. A.W. Kharche³

¹ Student of Department of Civil Engineering, Padm. Dr. V.B. Kolte College of Engineering, Malkapur, Dist- Buldana, 443101 Maharashtra, India.

² Assistant professor in department of Civil Engineering, Padm. Dr. V.B. Kolte College of Engineering, Malkapur, Dist- Buldana, 443101 Maharashtra, India.

³ Principal, Padm. Dr. V.B. Kolte College of Engineering, Malkapur, Dist- Buldana, 443101 Maharashtra, India.

DOI: 10.5281/zenodo.19237141

ABSTRACT

The design of steel structures has evolved from traditional experimental and analytical methods to sophisticated computational approaches. While classical engineering relied on closed-form solutions, modern urbanization and complex design constraints such as resilience against extreme loading have made these traditional methods impractical. Experimental studies remain vital but are often restricted by high costs and safety risks, especially concerning explosion scenarios. Consequently, Finite Element Methods (FEM) and numerical simulations have become indispensable tools, offering accurate approximations for complex structural behaviour.

This paper focuses on the performance of slender steel frameworks subjected to explosive blast loads. Blast-resistant design is now a critical priority due to rising accidental and intentional threats. The structural response to such events is highly complex, involving time-dependent effects, high strain rates, and material nonlinearities. This review evaluates the progression of modelling techniques from simplified single-degree-of-freedom (SDOF) systems to advance nonlinear finite element analysis highlighting their efficacy in modern "design for disaster" philosophies.

Keywords:- Structural Engineering, Slender Steel Frameworks, Blast-Resistant Design, Finite Element Method (FEM), Nonlinear Dynamics, High Strain-Rate, Numerical Modeling, Disaster Resilience

1. INTRODUCTION

Blast resistant doors have been designed with a variety of geometric shapes to suit the local conditions. The analysis of problems related to blast resistant doors subjected to explosive loads is not very new. But all the developments and knowledge in this field are made available mostly through classified documents published by defence organizations of the respective countries. In this field most of the research work was done by the leading educational institutions such as MIT, University of Illinois USA, University of Cape town in South Africa and few other research and development organizations due to specific projects given to these universities. In the design and analysis of structural steel plate with a variety of stiffeners subjected to varied blast loads calls for a thorough knowledge of blast phenomena. Further, it requires the dynamic response of various structural elements. There are two important design considerations in the analysis of blast resistant structures such as 1) structural dynamics and 2) blast aerodynamics. Particularly, in the design stages, the response of a structure for a dynamic load due to explosion is to be taken in to consideration more critically. Likewise, recognition of the blast loading behaviour such as peak pressure as well as time period (duration) of blast wave are the prerequisites for mechanical design and analysis. In the literature, there are a few studies on blast loading is available. But accurate assessment of these parameters such as peak overpressure is extremely difficult job. Failure of engineering structures is not uncommon when the structure is pushed to the limits of their performance capabilities as is the case during earthquakes, military or accidental explosions. An increased understanding of structural failure is necessary in order to reduce both the damage frequency (in care of multiple explosions) and severity.

2. LITERATURE REVIEW

Baker (1993) attempted, in the past, to characterize different forms of blast loadings resulting from various sources of explosions. The focus of the investigation was on the blast response of various structural systems that interests particularly for the marine and offshore industries. The structural systems in the present context are termed as energy dissipating barriers that dissipate blast energy.

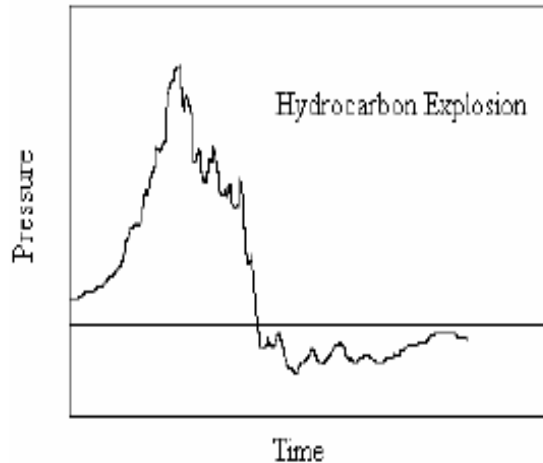


Figure 2.1 Typical pressure impulses for hydrocarbon explosion

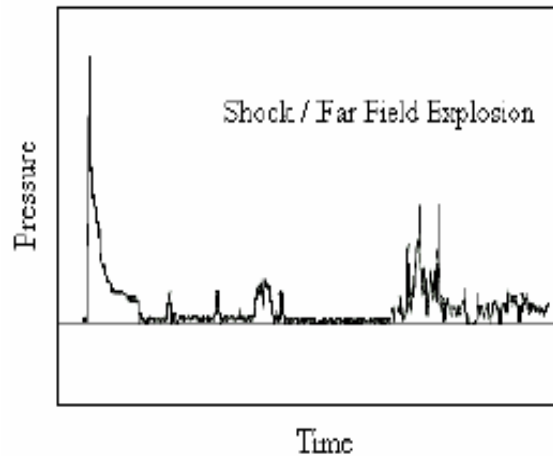


Figure 2.2 Typical pressure impulse for shock or far field explosion

Louca et al (2003), in their study, considered the loading on the structure with complex variations with time and also oscillations with varying frequencies. For the purpose of structural response calculation, simplifications are made. The negative phase of the pressure pulses is ignored although rebound can be significant when the negative pressure impulse is immediately preceded by a rapid decay rate of positive peak pressure or when explosion occurs below a floor panel supporting heavy equipment. Another assumption that often makes in structural response calculation is that the spatial variation of the pressure pulses on the targeted structure is negligible although this is often not true and can be unconservative in some cases.

3. RESEARCH GAP

The scientific and technical literature is very limited on the study of blast resistant steel structures. Further, major portion of the literature is classified in nature and is restricted for circulation amongst a few special groups. There are a few studies conducted by previous investigators using experimental and/or numerical methods. These studies distinguish different failure modes and establish the relationship between tearing and deformation of clamped blast loaded plates.

4. NEED FOR STIFFENED PLATES

In the present modern world, the demand for structures with high stiffness and low weight is increasing day by day. One of the ways to deal with the requirements is to use stiffeners on the plates. Large mechanical structures are generally composed of plates with stiffeners. The material of the plate and stiffener can be identical or different. The main advantage of using stiffened plates is their significantly high stiffness to weight ratio compared to unstiffened plates. Due to the increase in overall stiffness of the system, enhanced load carrying capacity and stability characteristics are obtained. So, it can be said that these are structurally efficient components that also have the added benefit of material savings and subsequent, economic and cost effective design. Another advantage of stiffened plates is that they can be fabricated with ease and simplicity. Hence, it is no surprise that such structural components find wide-spread utilization in modern branches of civil, mechanical, structural and construction engineering. Stiffened plates are subjected to various types of loading conditions in their working environment. For instance, in case of bridge decks the stiffened plates are under lateral or transverse loads. On the other hand, longitudinal bending of the ship hull exerts longitudinal in-plane axial compression on the plates. The loading conditions on a component can be broadly classified into two classes, static (invariant with time) and dynamic loading (varies with time). Hence, the design of the plates must be carried out keeping in mind these two aspects of loading. Considerations for static design include desired load carrying capacities and deformations within prescribed limits, while, design based on dynamic considerations deals with mechanical behavior with respect to time varying excitations.

5. LINEAR BUCKLING ANALYSIS

To comprehensively evaluate the blast resistance characteristics of stiffened and unstiffened plate structures, both linear buckling and nonlinear dynamic analyses are performed using ABAQUS. These analyses aim to capture the stability behaviour, deformation mechanisms, and energy absorption capacity of various configurations under different blast loading conditions. The approach integrates static stability evaluation with time-dependent dynamic response assessment to ensure a holistic understanding of structural performance.

The first stage of analysis involves linear eigenvalue buckling simulations, which are carried out to determine the critical buckling loads and corresponding mode shapes for circular plates reinforced with T-, H-, and I-shaped stiffeners positioned at different radial locations.

This analysis helps identify the structural stability limit before the onset of large deformations or failure. The eigenvalue buckling solver in ABAQUS computes the lowest eigenvalues (critical loads) that cause instability, along with their associated deformation modes.

6. METHODS FOR PREDICTION OF BLAST EFFECTS ON STRUCTURES

- ❖ Empirical methods
- ❖ Semi-empirical methods
- ❖ Numerical methods

Empirical methods are basically correlations with experimental data. These methods have certain limitations due to the fact that there is limited availability of experimental data. As the blast event becomes progressively near field, the accuracy of prediction of empirical equations reduces.

We get semi-empirical models, when the physical phenomenon is simplified with certain assumptions without losing the physics of the problem. These methods draw their strength from extensive data base and a number of case studies. The accuracy of prediction is generally comparable to that of empirical methods.

The foundations for numerical methods are differential equations that govern the basic laws of physics that describe a particular problem under consideration. These equations are generally laws of conservation of mass, momentum and energy. In addition, 4 constitutive relationships describe the physical behaviour of materials. Based on the application and load expected to be applied, the strength of the door is varied, which is designed based on the standard manual TM5-1300.

7. CONCLUSION

1. The response of steel structures under explosive loading is best addressed using advanced computational approaches that integrate blast loading characteristics with nonlinear structural dynamics.
2. While experimental blast testing remains the benchmark for validation, its practical limitations make Finite Element Method (FEM) simulations indispensable for studying high strain-rate effects and material nonlinearities.
3. Accurate blast-resistant design requires consideration of both peak overpressure and load duration; neglecting negative phase effects and spatial pressure variations may lead to unsafe structural predictions.
4. The blast performance of protective steel components is strongly influenced by geometric parameters, particularly stiffener thickness and stiffener layout density.
5. Parametric evaluation of stiffener thickness and plate curvature provides a reliable benchmark for validating numerical models and improving predictive accuracy.
6. The study supports a “design for disaster” approach, contributing toward the development of resilient steel infrastructure capable of withstanding extreme blast events.

8. REFERENCES

- [1] Wang, T. Dong, X. Wang, W. Zhang, X. Li, H. Diao, and Y. Fang, “Explosive dynamic response of steel-reinforced concrete-filled steel tubular columns under fire conditions,” *Developments in the Built Environment*, vol. 23, p. 100739, 2025.
- [2] C. Long and J. Jiang, “Study on the anti-progressive collapse behavior of steel frame structures under close-range blast loading,” *Buildings*, vol. 14, no. 5, p. 1387, 2024, doi: 10.3390/buildings14051387.
- [3] Anderson. C. E. Jr., O' Donaghue. P. E., Cox. P. A and Mullin. S.A., 1988, "Explosive Loading of Metal and Composite Panels: Comparison of Experiments and Numerical Simulations," Final Report, SwRI Project No. 06-1882/003, Southwest Research Institute, San Antonio, TX.
- [4] Akus. Y., Yildirim. R., 2004, —Effect of thickness on deformation of plates subjected to transient high pressures. I Proceedings of ESDA 2004: 7th Biennial Conference on Engineering Systems Design and Analysis, Manchester, United Kingdom, pp. 1-6.
- [5] Alexander. M., Remennikov., 2003, —A review of methods for predicting bomb blast effects on buildings, *Journal of battlefield technology*, vol 6, no 3. pp 155-161.

- [6] Argod. A., Nayak. S.K., Sing. A. K. and Belegundu. A.D., 2010, Shape optimization of Solid Isotropic Plate to Mitigate the Effects of Air Blast Loading| Mechanics Based Design of Structures and Machines. Vol. 38(3), pp 362-371.
- [7] Ari-Gur. J., Anderson. D.L. and Olson. M.D., 1983, —Air-Blast Response of Beams and Plates|, Report No 30, Dept. of Civil Engg., The University Of British Columbia Vancouver, Canada.
- [8] Assal. T. Hussein., 2010, —Non-Linear Analysis of SDOF System under Blast Load|., European Journal of Scientific Research., ISSN 1450-216X Vol.45, No.3, pp.430-437.
- [9] Baker. W.E., Cox P.A., Westine. P.S., Kulesz. J.J. and Strehlow R. A., 1983, —Explosion Hazards and Evaluation|. Elsevier.
- [10] Bangash. M.Y (England); Cambridge, Mass., USA: Blackwell Scientific Publications.
- [11] Bammann. D.J., Chiesa. M.L., Horstemeyer. M.F. and Weingarten. L.I., 1993, "Failure in Ductile Materials using Finite Element Methods," in Structural Crash worthiness and Failure, Jones N. and Weirzbicki T. Eds., pp. 1-54, Elsevier Science Pub.
- [12] Jain. R.K., 1973, —Axisymmetric Vibrations of Ring Stiffened Circular plates| Journal of Mechanical Engineering Science, Vol.15, pp.218-221.
- [13] Joshua. J. Israel., Andres Tovar., 2013 — Investigation of Plate Structure design under Stochastic Blast Loading| 10th World Congress on Structural and Multidisciplinary Optimization. May 19-24, Orlando, Florida, USA.
- [14] Jiang. J., Fagnan. J. R and Olson. M.D., 1993, —Amendment to Documentation for the Program NAPSSE, Department of Civil Engineering., The University of British Columbia, Vancouver, Canada.
- [15] Jiang. J and Olson. M.D., 1990, —Documentation for Program NAPSSE| Version 1.0, Department of Civil Engineering., The University of British Columbia, Vancouver, Canada.
- [16] Jennings. E., Grubbs. K., Zanis. C and Raymond. L., 1991, Inelastic Deformation of Plate Panels, Ship Structure Committee Report, SSC-364, pp. B1-B7.
- [17] Johnson. W., 1972, —Impact Strength of Materials|, Edward Arnold, London.
- [18] Jones. N., 1971, "A Theoretical Study of the Dynamic Plastic Behaviour of Beams and Plates with Finite Deflections," Int. J. Solids and Structures., Vol. 7, pp. 1007-1029.
- [19] Jones. N., 1975, "A Literature Review of the Dynamic Plastic Response of Structures," Shock and Vibration Digest, Vol. 7, No. 8, pp. 89-105.
- [20] Jones. N and Baeder. R. A., 1972, "An Experimental Study of then Dynamic Plastic Behaviour of Rectangular Plates," Symposium on Plastic Analysis of Structures, Vol. 1, pp. 476-497, Published by Ministry of Education, Polytechnic Institute of Jassy, Civil Engineering Faculty, Romania.
- [21] Jones. N., Uran. T and Terin. S.A., 1970, "The Dynamic Plastic Behaviour of Fully Clamped Rectangular Plates," Int. J. Solids and Structures., Vol. 6, pp. 1499-1512.
- [22] Jones. N., 1976, "Plastic Failure of Ductile Beams Loaded Dynamically," J. Eng. Ind., Trans. ASME, Vol. 98, pp. 131-136.