International Journal of Scientific Engineering and Technology Research

ISSN 2319-8885
Vol.02,Issue.09,
September-2013,
Pages:927-934

www.semargroups.org,
www.ijsetr.com

Analysis of Plates Subjected to Blast Loads

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Abstract: This study is concerned with the numerical study of fully fixed stiffened plates. The aim of this research is to determine the dynamic response of the plates with different stiffener configurations and considering the effect of standoff distance. Numerical solutions are obtained by using the finite element method and the central difference method for the time integration of the nonlinear equations of motion. Special emphasis is focused on the evolution of mid-point displacements, von mises stresses and strain energy vs. kinetic energy. The results obtained allow an insight into the effect of stiffener configurations and of the above parameter on the response of the plate under uniform blast loading and indicate that stiffener configurations, standoff distance and time duration can affect their overall behavior. From the study, it is observed that the stiffeners effectively sustain the blast pressure, and the cover plat with HAT stiffener can sustain stresses more than the plate with T and I stiffener, and are deformed with less relative displacement.

Keywords: blast loading, stiffened door structure, explosion.

I. INTRODUCTION

Natural and unexpected disasters have always attracted the attention of scientist and engineers like earthquake etc. The blast problem is new; information about the development in this field is made available mostly through publication of the Army Corps of Engineers, Department of Defense, U.S. Air Force and other governmental office and public institutes. Substantial R&D has been done by the Massachusetts Institute of Technology, The University of Illinois, and other leading educational institutions and engineering firms. Due to different accidental or intentional events, the behavior of various structural components subjected to blast loading has been the subject of considerable research effort in recent years. Conventional structures, particularly that above grade, normally are not designed to resist blast loads; and because the magnitudes of design loads are significantly lower than those produced by most explosions, conventional structures are susceptible to damage from explosions. With this in mind, developers, architects and engineers increasingly are seeking solutions for potential blast situations, to protect building occupants and the structures.

Ming-Wei Hsieh et al. [1] studied the effect of blast load on a stiffened door structure by varying height and thickness of the stiffener. The door is designed to provide least damage to its occupants and contents, and the damage extent is restricted by the protection level prescribed [16]. For this, a series of transient analysis were performed to predict the dynamic response of blast resistant doors. A. Khadid et al. [2] studied the fully fixed stiffened plates under the effect of blast loads to determine the dynamic response of the plates with different stiffener configurations and considered the effect of mesh density, time duration and strain rate sensitivity. In this paper, the finite element method and the central difference method are used for the time integration of the nonlinear equations of motion to obtain numerical solutions. R. Rajendran et al. [3] studied the effect of different blast loads on plates which are the common elements of various structures.

These structures may be land based which may be subjected to air blast during combat environment or terrorist attack, while marine structures may be subjected air blast or under-water explosion by the attack of a torpedo or a mine or a depth-charge and an effect of on-board explosive devices on aircraft structure. Further-more, the effect of gas-explosion on off-shore installations and industries is also studied. T. Ngo et al. [4] studied the effect of a bomb explosion within or immediately near a building which causes a catastrophic damage on the building's external and internal structural frames. In this paper, a comprehensive overview of the effects of explosion on structures is also presented. An explanation of the nature of explosions and the mechanism of blast waves in free air is also given, along with different methods to estimate blast loads and structural response. J

Zamani et al. [5] studied the dynamic plastic response of structures under blast loading and underwater explosion which has found important applications in the design of energy-absorbing and collision protection devices. In this paper, the results on the response of steel, and aluminum fully clamped circular plates, in two different media of air and water presented. The effect of material and medium is also investigated.

C. M. Ewing et al. [6] studied the possibility of controlling the response of typical portal frame structures to blast loading using a combination of semi-active and passive control devices. In this paper, the model structure is subjected to blast loads of varying duration, magnitude and shape, and the critical aspects of the response are investigated over a range of structural periods in the form of blast load response spectra.

Assal T. Hussein [7] presented the analytical methods of a SDOF system analysis subjected to blast loadings. Two types of blast waves were applied to study the non-linear behavior of system, focused on displacement time history responses which form the basis for studying behavior of SDOF system under blast loadings.

Wen Chen et al. [8] applied the compound strip method to the buckling analysis of ring stiffened cylindrical shells under hydrostatic pressure. Comparisons are made between buckling loads of shells stiffened by traditional T-shaped stiffeners and the HAT-shaped stiffeners. Nelson Lam et al. [9] further developed the existing knowledge on the modeling of blast pressure in engineering applications. In this paper, a simple and yet realistic capacity spectrum model has been developed for the design and assessment of cantilevered walls for its performance under blast loads.

Regarding the failure analysis of blast resistance structure, most researches had paid attention on investigating the performance of stiffened or un-stiffened metal plates of small scale. For example, Nu- rick et al. [11,12] and Rudrapatna el al. [13], respectively, reported the possible failure modes of a stiffened plate under explosive pressure by means of numerical and experimental investigation. Their works indicated that the plate structure might fail in different modes depending on the loading conditions applied on the plate, while the stiffener size was proven to have no profound effect on the failure modes. Louca et al. [14] also presented comparison investigations on the dynamic response of stiffened and unstiffened plates by numerical method. The results showed that the effect of the boundary conditions on the dynamic response was significant. Zhu [15] predicted the transient deformation of unstiffened square plates made of various materials under explosive loadings and compared the numerical results with experimental investigation based on optical techniques. However, in commercial application for civilian buildings, a large scale door structure should have sufficient capacity to resist the blast loads in an actual event. Keeping this in view, a door structure of special-duty type was designed of 1.2 m x 1.2 m with plate thickness of 16 mm. Three types of stiffeners namely T, I and HAT stiffeners are used for stiffening the panel along the vertical and transverse span. The stiffeners are designed to have almost the same magnitude of moment of inertia 1.3 x 10^{-6} m^4. The door is subjected to blasting load of 250 kg of TNT at various distances (1 and 10m).

For a long time, the technology development of blast-resistant structure was aimed at military facilities and could not be accessed for general application in industry. Recently, with the advancement in computer technology, a lot of analysis software packages have been developed by implementing the theoretical mechanics into finite element method (DYNA, NASTRAN, DYTRAN, ANSYS, NISA, ABAQUS, etc), which can provide an efficient tool in analyzing the dynamic behavior of complicated structures. This study was therefore aimed to investigate the blast resistance of a door structure with stiffeners by using finite element analyses. This approach can be used for simulating the effect of structural modification on the anti-blast capability and is expected to help the structural engineer to design other blast-resistant facilities.

II. THE WAVE PROPAGATION OR EXPLOSION PROCESS

The explosion process is divided into two parts:

1) The detonation process.
2) The interaction process between the product gases and the surrounding medium (air in atmosphere and water in Underwater).

During the detonation process, a detonation wave generates and propagates in the explosive. Once the process of detonation is completed, the interaction of the product gases with the surrounding medium takes place. The product gases with high pressure and temperature expand outward by generating a pressure wave. The gaseous products are assumed to be in viscid at this high temperature and thus the viscous forces are not considered for the explosive modeling. In the water medium, an instantaneous compression of the water surrounding the gas emits a pressure pulse that propagates into water with a velocity that is three times higher than the velocity of sound in water.

III. CHARACTERISTICS OF BLAST WAVE

In the design of blast door, the structural dynamic behavior responding to explosive loads should be investigated in detail. The blast effects are described as the shock wave of high-pressure shock front impinging on the target and then decaying with time. Prior to analyses, it is therefore necessary to establish the properties of a blast wave such as peak overpressure, reflected peak pressure and loading duration. These properties are highly dependent on the explosive charge weight, detonation distance to target, geographical surrounding and atmospheric pressure. The details of the blast characteristics for a variety of explosives can be enquired from empirical charts or formulae in military technical manual TM5-1300 [16], blast effect analysis software [17] or statistical analysis [18,19, 20] during design procedure. As an example in [21], the peak overpressure Ps and duration of positive pressure ts can be expressed as the function of the scaled distance Z and explosive charge weight W, respectively. That is,

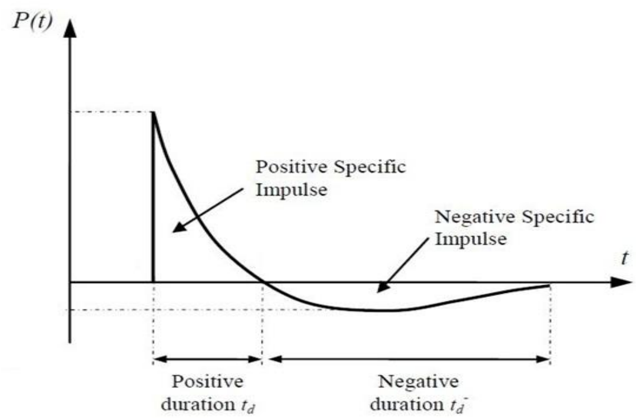


Figure1. Time history of a typical blast wave pressure and Idealized triangular wave.

$$\frac{P_s}{P_0} = \frac{808\left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{Z}{0.048}\right)^2}\cdot\sqrt{1+\left(\frac{Z}{0.32}\right)^2}\cdot\sqrt{1+\left(\frac{Z}{1.35}\right)^2}} \quad (1)$$

$$\frac{t_s}{W^{1/3}} = \frac{980\left[1+\left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.002}\right)^3\right]\cdot\left[1+\left(\frac{Z}{0.74}\right)^6\right]\cdot\sqrt{1+\left(\frac{Z}{6.9}\right)^2}} \quad (2)$$

Where P_0 is the atmospheric pressure (bar) and the scaled distance parameter Z is a measure to compare the blast effect generated from different explosions, which is attributed to Hopkinson [22] and is given by the form $Z = R/W^{1/3}$ (R and W are the standoff distance from detonation to the target). The peak reflected pressure P_{max} can be obtained from the following equation [23].

$$P_{r\,max} = \frac{2P_{max}(710+4P_{max})}{710+P_{max}} \quad (3)$$

Here P_{max} is the peak overpressure of the shock wave. Besides, a definition describing the variation of the blast pressure as a function of time is required for dynamic analysis. For this, many mathematical models were developed, in which the simplified single impulse-duration relation of triangular shape was mostly used to simulate the experimentally obtained pressure-time history [24] (see Fig. 1), that is,

$$P(t) = P_{max}\cdot\left(1-\frac{t}{t_d}\right) \quad (4)$$

In which t_d is the duration of the blast wave for triangular loading representation, P_{max} represents the peak pressure of the shock wave in positive phase or negative phase.

IV. BASIC SPECIFICATION OF BLAST DOOR AND STIFFENERS

Blast resistant doors are normally designed with enough load carrying capacity to resist a high pressure shock front of very short duration. The essential dimensions of the blast door used in this study are 1200 mm in width and 1200 mm in height, in which the cover plate has a thickness of 16 mm. For the stiffener the dimensions are as shown in Figure 2. As the comparison is between the stiffeners performance, all the three types of the stiffeners are designed to have almost the same magnitude of moment of inertia (1.3×10^{-6} m^4).

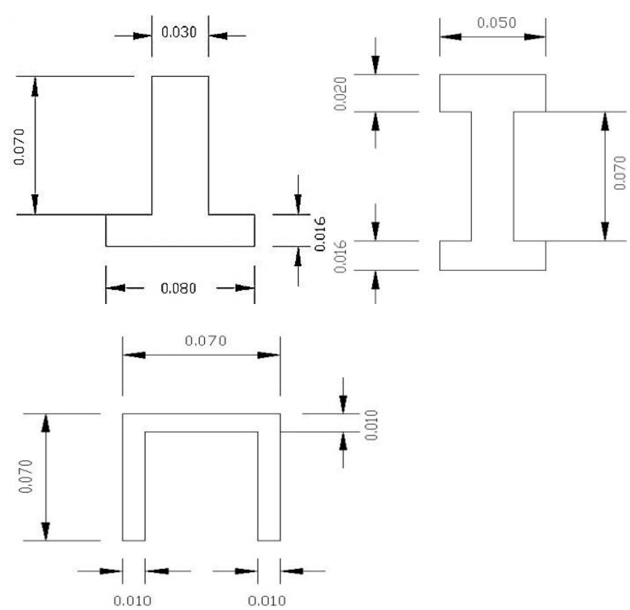


Figure2. Schematic of the stiffeners (all dimension in M).

The material for cover plate and stiffeners is chosen from a manual which is specially designed by Department of the Army, “Structures to resist the effects of accidental explosive," TM5-1300, Washington, D.C. (1990). The materials chosen are,

ASTM A515 Grade 50 Material for Cover Plate	ASTM A36 Steel Material for Stiffener
• Young's Modulus, E = 200 x 10^9 N/m^2 • Poisson ratio, ν = 0.3 • Density, ρ = 7830 kg/m^3 • Static yield, σ yield = 265 x 10^6 N/m^2 • Ultimate Tensile strength, σ_{ut} = 492 x 10^6 N/m^2	• Young's Modulus, E = 200 x 10^9 N/m^2 • Poisson ratio, ν = 0.29 • Density, ρ = 7800 kg/m^3 • Static yield, σ yield = 248 x 10^6 N/m^2 • Ultimate Tensile strength, σ_{ut} = 400 x 10^6 N/m^2

V. BLAST LOADING

The blast load characteristics are calculated as follows:

- Weight of TNT (explosive), W =250 kg.
- Scaled distance, $Z = \frac{R}{W^{\frac{1}{3}}} = \frac{10}{250^{\frac{1}{3}}} = 1.59$.

$$\frac{P_{max}}{P_o} = \frac{808\left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{Z}{0.048}\right)^2}.\sqrt{1+\left(\frac{Z}{0.32}\right)^2}.\sqrt{1+\left(\frac{Z}{1.35}\right)^2}}$$

$$= \frac{808\left[1+\left(\frac{1.59}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{1.59}{0.048}\right)^2}.\sqrt{1+\left(\frac{1.59}{0.32}\right)^2}.\sqrt{1+\left(\frac{1.59}{1.35}\right)^2}} = 3.52 \text{ bar}$$

$$= 3.52 \times 10^5 \text{ Pa.} \qquad (6)$$

$$\frac{t_s}{W^{\frac{1}{3}}} = \frac{980\left[1+\left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.002}\right)^3\right]\left[1+\left(\frac{Z}{0.74}\right)^6\right].\sqrt{1+\left(\frac{Z}{6.9}\right)^2}}$$

$$= \frac{980\left[1+\left(\frac{1.59}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{1.59}{0.002}\right)^3\right]\left[1+\left(\frac{1.59}{0.74}\right)^6\right].\sqrt{1+\left(\frac{1.59}{6.9}\right)^2}} = 6 \times 10^{-3} s \qquad (7)$$

From the calculation of the load for 250 kg of TNT at 1m and 10m standoff distances we got a load with respect to time as shown below:

TABLE1: Shows the varying of pressure with respect to time.

$P_{(t)}$ (MPa) at standoff distance 10m	0	0.352	0.352	0
t_s (milli sec)	0	0.5	3.5	6

The plate will be subjected to a load that varies with time; Figure 3 shows only the positive peak overpressure and its decline with respect to its positive time duration because the positive phase is more interesting in studies of blast wave effects on structures because of its high amplitude of the overpressure and the concentrated impulse.

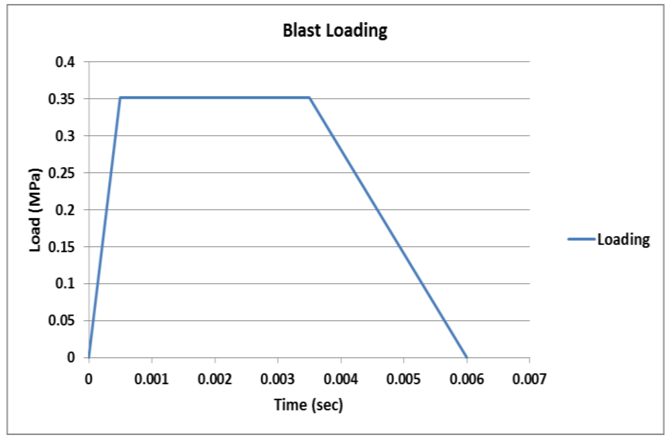


Figure3. The positive duration of load with respect to time.

VI. RESULT AND DISCUSSION

A. Von Mises Stresses

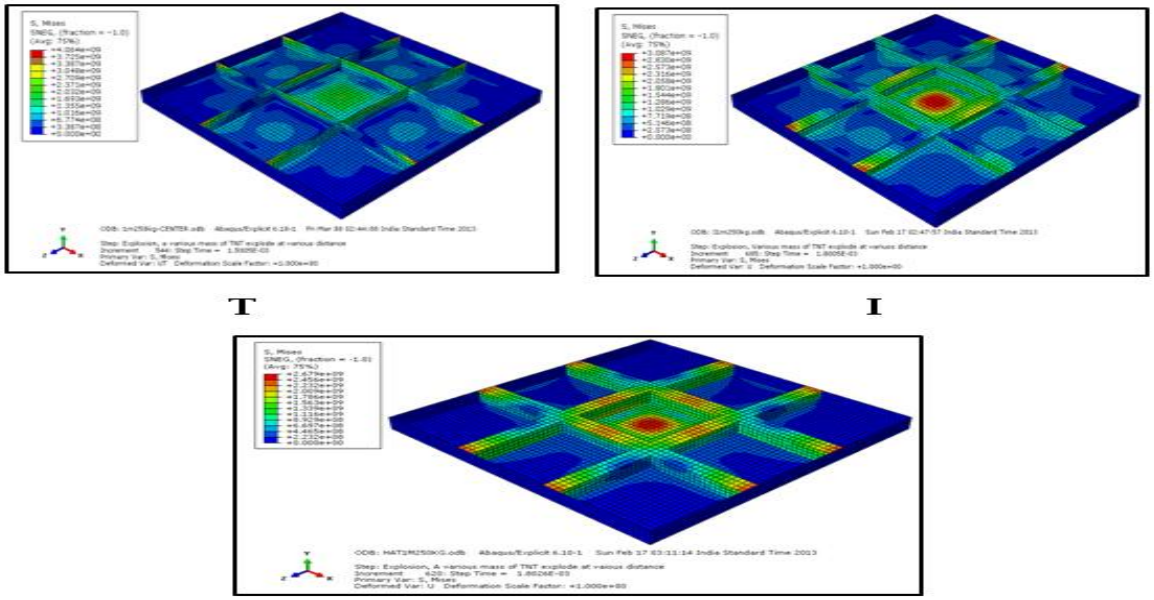
Von Mises stress is used as a criterion in determining the onset of failure in ductile material. The failure criterion states that the Von Mises stress should be less than the yield stress of the material[10]. The maximum Von Mises stress at highly stresses regions of the cover plate with the stiffeners are tabulated and shown in table (2) & (3).

TABLE2. Results of cover plate with the stiffeners at standoff distance 1m.

Stiffener Type	Mass of TNT (kg)	Max. V.Mises stress (MPa)		Max Disp. (mm)
		Cover Plate	Stiffener	
T	250	3232	4606	44.3
I	250	3087	3088	31.6
HAT	250	2679	2681	26.8

TABLE3. Results of cover plate with the stiffeners at standoff distance 10m.

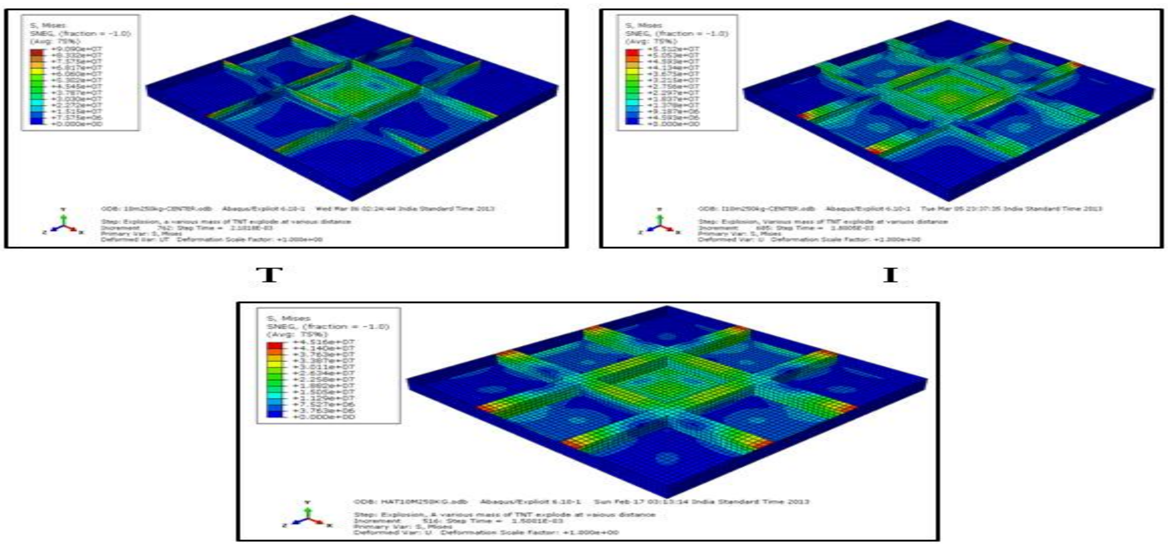
Stiffener Type	Mass of TNT (kg)	Max. V.Mises stress (MPa)		Max Disp. (mm)
		Cover Plate	Stiffener	
T	250	66.2	90.9	0.948
I	250	55.06	55.12	0.536
HAT	250	41.08	45.19	0.461



T I

HAT

Figure4. Contour plots for V.Mises stresses (at standoff distance 1m).



T I

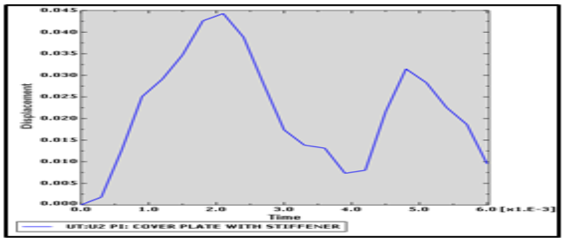
HAT

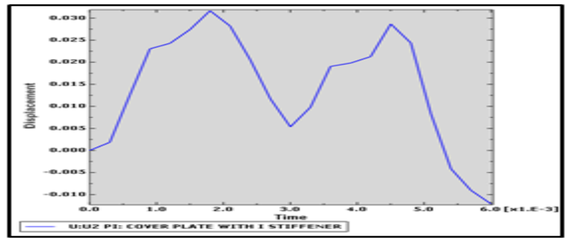
Figure 5: Contour plots for V.Mises stresses (at standoff distance 10m).

The stress contour plots clearly indicate that the T, I and HAT stiffeners effectively sustain the blast pressure. The tables (2) and (3) summarize the peak Von Mises stress of cover plate with stiffeners for door structure, in which the cover plate is assumed to be fully fixed. It is observed that by using the HAT stiffener, can remarkably increase the rigidity of door structure and reduces the Von Mises stress generated in the stiffeners. In addition, the predicted peak Von Mises stress for the stiffeners and the plates in the case of 1m distance from the explosive are apparently higher than the yielding strength and ultimate tensile strength of the materials. It is also observed that, the stress induced on the central region of the cover plate is lower than its strength, indicating the initiation of local yielding at these locations, rather than the whole structure.

B. Mid-Point Displacement

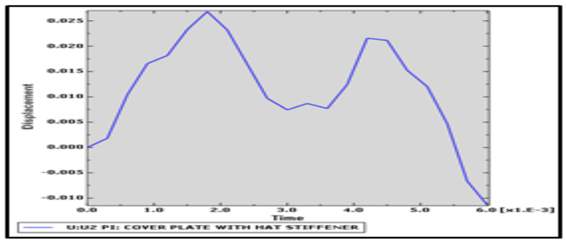
The figures (6) and (7) show the maximum displacements plots at the center node of the plate for T, I and HAT stiffeners.





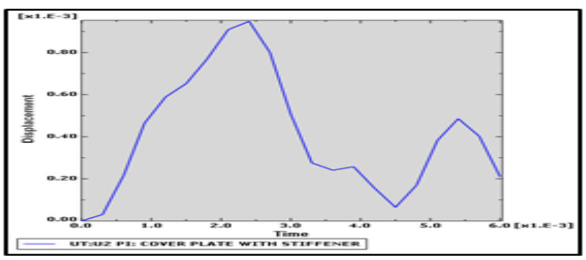
T

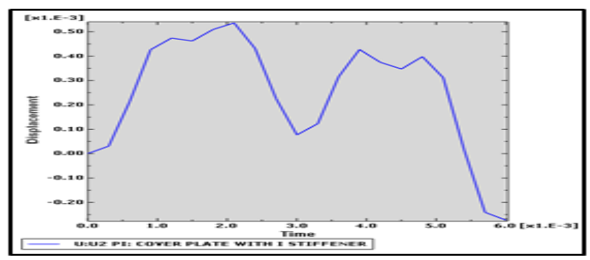
I



HAT

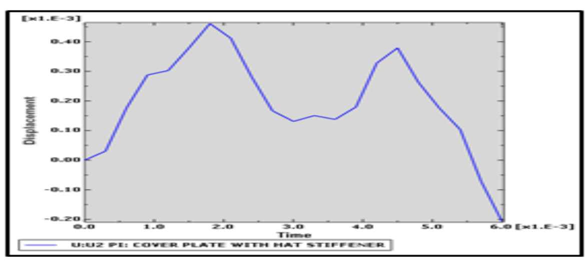
Figure6. Displacement in M at the mid-point of the plate (at standoff distance 1m).





T

I



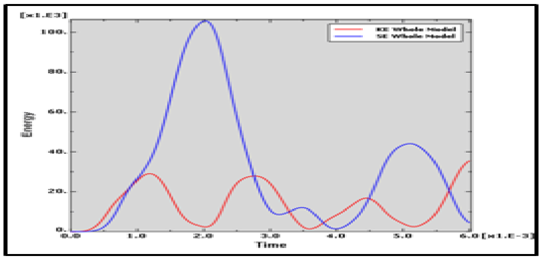
HAT

Figure7. Displacement in M at the mid-point of the plate (at standoff distance 10m).

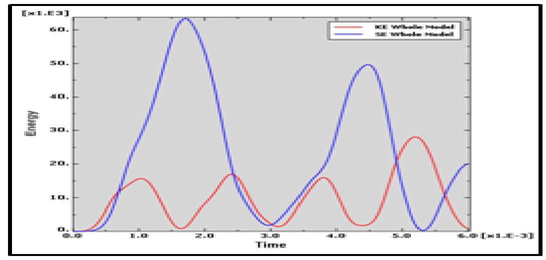
The mid-point displacement is considered at the center node here because the blast load is applied at the center of the cover plate. The mid-point displacement for cover plate with T, I and HAT stiffeners are plotted with respect to time for the figures (6) and (7). It's observed that the maximum displacement in T shaped is more than 80 x 10^{-3} m and more than 50 x 10^{-3} m in I shaped which is less than the displacement in HAT stiffeners, 40.6 x 10^{-3} m for the case of 250 kg of TNT at 10 m distance. Hence it can be observed from graphs that HAT shaped stiffener shows less mid-point displacement than T and I shaped stiffeners.

C. Energy

The figures (8) and (9) show the strain energy and kinetic energy plots for T, I and HAT stiffeners. The kinetic energy of the impacting body will be partially converted to strain energy in the target and partly dissipated through friction and local plastic deformation and strain energy radiated away as stress waves. When the plate is at its maximum deflection and, therefore, has its maximum strain energy, it is almost entirely at rest, causing the kinetic energy to be at a minimum. The strain energy of cover plate with T, I and HAT shaped stiffeners



T



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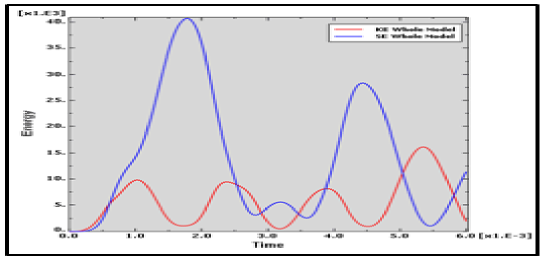
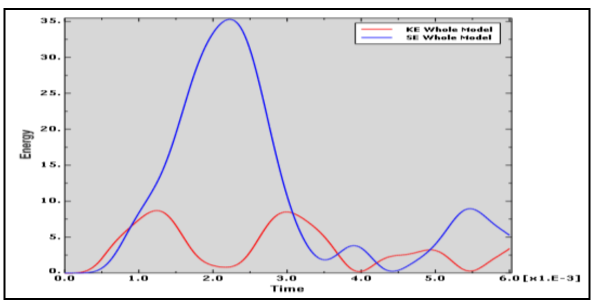
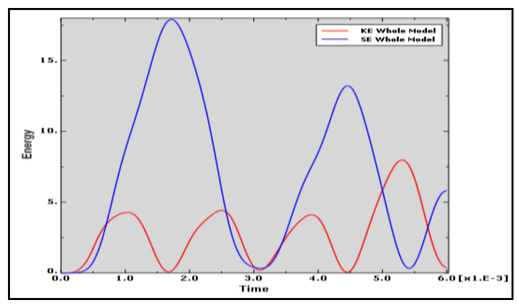


HAT

Figure8. Energy (kN.m) vs. Time (s) (at standoff distance 1m)



T



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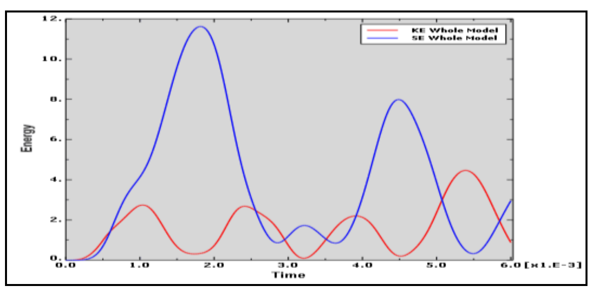

HAT

Figure9. Energy (kN.m) vs. Time (s) (at standoff distance 10m).

are plotted with respect to time in figures (8) and (9). It is observed from the figs that the strain energy in T shaped is more than 100KN.m at 1m distance and more than 35KN.m at 10m distance and for the I stiffener is more than 60KN.m at 1m distance and more than 15KN.m at 10m distance for 250 kg of TNT which are more than the strain energy in HAT shaped, just more than 40KNm and more than 10KN.m for 1m and 10m standoff distance respectively for 250 kg of TNT. Hence it can be observed from graphs that HAT shaped stiffener shows less strain energy than T and I shaped stiffeners.

VII. CONCLUSIONS

From the dynamic/explicit finite element analyses carried out to examine the behavior of fully fixed stiffened plates under blast loading, the following conclusions can be drawn:

- Using I stiffener instead of T stiffener, can reduce the von mises stress by 17% that generated in the cover plate and by 40% that generated in the stiffeners (at 10 m standoff distance and 250 kg of TNT).
- While using the HAT stiffener instead of T stiffener, can remarkably reduce the von mises stress by 38% that generated in the cover plate and by 50% that generated in the stiffeners (at 10 m standoff distance and 250 kg of TNT).
- The mid-point displacement at the center node of the cover plate is reduced by 44% when I stiffener is used and reduced by 51% when HAT Stiffener is used instead of T stiffener (at 10 m standoff distance and 250 kg of TNT).

- The strain energy in the cover plate with I and HAT stiffener is less by 50% and 66% respectively, than the strain energy in the cover plate with T stiffener (at 10 m standoff distance and 250 kg of TNT).
- From the analysis, the cover plate with HAT stiffener is found to offer more resistance compared to T and I stiffeners for blast loads.

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