Dynamic Response of Hastelloy[®] X Plates under Oblique Shocks: Experimental and Numerical Studies

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Abstract

The dynamic behavior of Hastelloy[®] X plates subjected to normal and oblique shock loading was studied both experimentally and numerically. A series of experiments was conducted on Hastelloy[®] X plates at room temperature under fixed boundary conditions using a shock tube apparatus. High-speed digital cameras were used to obtain the real-time images of the specimen during the shock loading. Digital Image Correlation (DIC) technique was utilized to obtain 3D deformations of the plates using stereo-images of the specimen. The numerical modeling utilized the finite element software package Dynamic System Mechanics Analysis Simulation (DYSMAS) which includes both the structural analysis as well as the fluid-structure interaction to study the dynamic behavior of the specimen under given loads. Experimentally obtained pressure-time profiles were used as a reference in numerical modeling. It was observed that the lower angles of shock incidence caused more deformation on the specimen. Additionally for oblique shocked specimens, the deformation was observed to initiate from the edge nearer to the muzzle. The results from the numerical simulations were validated with the experimental data, and showed excellent correlation for all cases.

76 **Keywords**

77 *Hastelloy[®] X, Oblique shocks, 3D Digital Image Correlation (DIC), High-speed photography,*
78 *Numerical simulation*

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1. Introduction

An experimental and numerical study was conducted to understand deformation in a superalloy Hastelloy[®] X when subjected to normal and oblique strong shock wave loadings. The experiments incorporated real-time diagnostics to understand the structural behavior of Hastelloy[®] X plates. The numerical simulations included fluid-structure interactions in the dynamic analysis of the problem.

The study is motivated by the need to understand response of aerospace structures to highly dynamic strong shock loadings at various angles of incidence. There are few materials that come close to fulfilling the stringent requirements placed on aerospace structures that operate under extreme conditions of loadings. These extreme conditions include highly dynamic loads, extreme temperatures and pressures and other environments. One class of materials that have shown promise for such applications are nickel based superalloys including Hastelloy[®] X. This material shows high oxidation resistance, machinability, and has the capability of retaining its strength to a greater extent at high temperatures [1,2].

Many researchers have studied, both experimentally and numerically, the behavior of monolithic plates subjected to shock loading. The classic experimental work of Menkes and Opat [3] on the clamped aluminum beams subjected to shock loading identified three damage modes namely mode-I (inelastic deformation), mode-II (tearing at the extreme fiber) and mode-III (transverse shear at the support). The subsequent experimental studies of Teeling-Smith and Nurick [4], Nurick and Shave [5], Olson et al. [6] and Shen and Jones [7] reported the same kind of failure modes when a structure is subjected to blast loading. The experimental and numerical investigation of Nurick et al. [8], Chung Kim Yuen and Nurick [9] and Langdon et al. [10] shed

some light on the effect of stiffeners and their configuration on the blast loading of stiffened plates. Balden and Nurick [11] performed the numerical simulations to differentiate the deformation, post-failure response of uniform and localized blast loaded plates. In recent years many researchers used numerical methods to understand this complex problem [12-16]. Very recently, Abotula et al. [17] conducted a series of experiments to investigate the response of simply supported Hastelloy[®] X plates subjected to shock loading at temperatures up to 900 °C. They found that the maximum deflection of the plate increased with the temperature and was 160% higher at 900 °C when compared to that at room temperature. All these studies focused on normally incident shock loadings on the structures. . Gray et al. [18] have used direct detonation-wave shock loading on metallic plates. They have found increased shock hardening and twin formation with increasing shock obliquity. Aerospace structures are often subjected to long duration oblique shocks that last a few milliseconds and thus, there is need to understand the response of aerospace materials under these loads.

The experiments in this study utilized 3D DIC technique coupled with high speed photography to measure the out-of-plane deflections of the specimen for 0°, 15° and 30° incident angles. The investigation was further extended using DYSMAS to study the response for 45° and 60° incident angles. Experimental results are utilized to validate the numerical model. The results manifest more deformation at lower angles of incidence. In case of oblique shocked specimens, the deformation initiates from the edge closer to the shock tube muzzle. The peak out-of-plane deflection is observed to vary nonlinearly.

2. Experimental procedure

A series of experiments was carried out to study the dynamic deformation of plates subjected to normal and oblique shocks. Hastelloy® X was selected as a material of choice for the experiments due to its exceptional performance compared to typical structural steels.

2.1. Material, specimen geometry and boundary conditions

Hastelloy® X is a nickel based superalloy with high oxidation resistance, good machinability and high-temperature strength. Table 1 provides the chemical composition of the material. The presence of a high percentage of Ni imparts good strength even at elevated temperatures. Chromium is responsible for the high oxidation resistance. Typical physical properties of this material are given in Table 2. The dynamic constitutive behavior of Hastelloy® X was recently investigated [2] and the Johnson-Cook (J-C) parameters were reported as shown in Table 3. This J-C plasticity model was used in the numerical investigation. The Johnson-Cook (J-C) plasticity model incorporates Mises plasticity criteria with analytical forms of the hardening law and rate dependence. J-C model has been found suitable for computations of high-strain-rate deformation of most metals.

The monolithic Hastelloy® X plates used in this study have a length of 203 mm, width of 51 mm and thickness of 3 mm. Since the main objective of this study is to investigate the response of monolithic Hastelloy® X plates subjected to oblique shocks, a clamped boundary condition was used at the top and bottom of the specimen. The vertical edges of the specimen were unsupported. The details of specimen and boundary conditions can be seen in Fig. 1(a). The unsupported length of specimen was 152 mm.

2.2. Experimental arrangement

Experiments were conducted to understand the behavior of Hastelloy[®] X plates subjected to shock wave with an angle of incidence (angle between the incident shock front and the reflecting surface) of 0° (normal shock), 15° and 30°. These incident angles were obtained by deflecting the specimens at angles 90°, 75° and 60° respectively with shock tube axis. For each shock incident angle, three experiments were conducted to ensure repeatability of the results. The schematic top-view of the experimental setup with different angles of incidence is shown in Fig.1 (b).

2.3. Shock wave loading apparatus

In a laboratory environment, highly controlled shock waves can be easily generated using a shock tube. The shock tube apparatus used in this study is a horizontally mounted, compression-driven shock tube. Fig. 2(a) shows the University of Rhode Island (URI) shock tube facility with an overall length of 8 m. It consists of a driver section and a driven section separated by a diaphragm. The driver section has an inner diameter of 152.4 mm and the driven section has straight components besides two convergent sections, one varying from 152.4 mm to 76.2 mm and another from 76.2 mm to 38.1 mm, with a final muzzle diameter of 38.1 mm. In this study, a Mylar[™] sheet of thickness 10 mil (0.254 mm) was used as diaphragm. The driver section was supplied with high pressure helium gas and the driven section contains air at ambient pressure. When the driver and driven gas pressure difference reaches a critical value, the diaphragm ruptures causing a shock wave propagating down the driven section. As soon as the incident shock wave encounters the specimen, the high kinetic energy possessing particles in the shock front abruptly come to rest and get reflected. This results in a reflected wave which is higher in magnitude than the incident wave.

Three high frequency pressure transducers (PCB102A) were mounted at the end of the driven section as shown in Fig. 2(b) in order to obtain the incident and reflected pressure histories. The speed of the shock wave was calculated knowing the distance between any two transducers and the time taken by the shock wave to pass that distance. The diaphragm used in this study resulted in an incident pressure of 0.5 MPa and an incident shock wave velocity of 880 m/s (Mach 2.6).

2.4. High-speed photography system

The dynamic response of the specimen subjected to shock loading was captured with a high-speed photography system consisting of three Photron SA1 high-speed digital cameras. The 3D deformation behavior was obtained using 3D Digital Image Correlation (DIC) technique. The 3D DIC is an optical, non-contact method based on the stereo image triangulation. The two cameras shown in back-view camera system of Fig. 3 were used to obtain stereo images of the back-face of the random speckle patterned specimen. In order to capture the side-view deformation images, a third high-speed digital camera was employed as shown in Fig. 3. The frame rate used was 50,000 fps (interframe time is 20 μ s) with an image resolution of 192 x 400 pixels. All the cameras were synchronized so that the images can be correlated. The oscilloscope was triggered with the pressure signal from the incident shock wave, which further sends a signal to trigger the cameras.

3. Computational modeling

Computational simulations of the shock loading events were performed with the Dynamic System Mechanics Analysis Simulation (DYSMAS) software. This software is developed and maintained by the Naval Surface Warfare Center, Indian Head. It consists of an

Eulerian fluid solver, GEMINI, a Lagrangian structural solver, ParaDyn, and an interface module which couples the two. GEMINI is a high order Eulerian hydrocode solver for compressible, inviscid fluids. ParaDyn (parallel version of DYNA3D) is a Lagrangian non-linear, three dimensional explicit finite element code for structural applications. The interface module is a standard coupler interface which allows the fluid and structural codes to share the required variables for the fluid structure interaction problem.

The computational models were built so as to capture the fluid structure interaction between the shock front developed in the shock tube and the Hastelloy[®] X plates. The models consist of the shock tube wall, the Hastelloy[®] X specimen, mounting fixture representation and the air within and external to the tube walls. The model results were compared to the experimental data and the correlations are discussed later in the paper.

3.1. Structural model

The structural model consists of the shock tube wall, the Hastelloy[®] X plates, and an appropriate representation of the mounting fixture. The parts were modeled with half symmetry with the upper half of the plates being modeled and the axis of the shock tube along the Z-axis. Although the specimens in the case of 0° angle of incidence also exhibit symmetry about the vertical (left/right) plane, this was not the case for the specimens subjected to oblique shocks. Therefore, a one-half symmetry model was used for all geometries. The plate, tube wall, and fixturing were modeled with shell elements, which have 5 integration points through the thickness. The mid-surface of the specimens was modeled, while the inner surface of the shock tube wall was meshed. The Hughes-Liu element formulation was used for all elements, which for the shock tube wall and fixturing allows for a shell thickness offset to be applied so that the

appropriate surface may be modeled. The Hastelloy[®] X plate was modeled with the Johnson-Cook Elastic-Plastic (Type 15) model with the parameters, Table 3, taken from quasi-static and high strain rate data. The shock tube walls and test fixturing were modeled with rigid material definitions. The specimen was modeled using quadrilateral elements with 1 mm edge lengths and a shell thickness of 3.175 mm. The elements comprising the shock tube wall have an edge length of 1 mm and a thickness of 19.05 mm.

3.2. Boundary conditions

The boundary conditions applied to the model were representative of those applied in the experiments for the clamped conditions. In all models the shock tube walls were fully constrained as they were assumed to be sufficiently rigid with minimal outward radial expansion during the travel of the incident shock wave. Additionally, symmetric boundary conditions were applied to the bottom edge of the model which represents the horizontal mid-plane of the specimens. The symmetry boundary condition restricts the vertical translation of these nodes and the rotations about the two horizontal axes.

During the clamped boundary condition experiments it was observed that the clamping force along the top edge was not sufficient to prevent the panel from slipping in the fixture. The clamping force however was able to prevent rotations along this edge. Therefore fully clamped conditions along this edge cannot be realistically applied in the simulation without over constraining the model. In lieu of fully clamped conditions a combination of explicitly modeling the outer bolt surface and translational constraints were applied, Fig. 4. The outer surfaces of the clamping bolts were modeled (zero contact thickness applied) and contact was established between the inner surface of the plate holes and the surface of the bolts. The gap between the

bolt surface and the inner hole edge corresponds to the bolt clearance in the experimental setup. Additionally, the nodes which correspond to the plate surface between the clamping plates were restricted from any out-of-plane motion. This combination of bolt contact and out-of-plane translational constraints allow the observed in-plane slippage to be accounted for by constraining the nodes to move in the plane of the panel until contact occurs with the bolts, while also preventing rotation and out-of-plane motion.

Fig. 5 shows the orientation of panels with respect to the shock tube muzzle. Each panel is oriented such that the centerline of the plates is aligned with the center line of the shock tube and that the 3 mm gap between the plate and the shock tube corresponds to the point of closest approach.

3.3. Fluid model

The fluid model consists of the air internal and external to the shock tube as well as the air surrounding the plate. The fluid domain was rectangular with a domain size of 200 mm in the vertical direction, 250 mm in the horizontal direction, and 3500 mm in the shock tube axis. There was 500 mm (along the shock tube axis) of air behind the plate to ensure that it remains in the fluid domain during the deformation event. Internal to the shock tube walls there were 20 fluid cells in the radial directions for a cell size of 1 mm. These cells were then tapered starting at the shock tube wall from 1 mm to 2.5 mm at the domain boundary. Along the tube axis the cells have an initial size of 5 mm at the end opposite of the plate and were refined to 2.5 mm over 2500 mm in tube length. The cells have a size of 2.5 mm for the remainder of the fluid domain in the axial direction including the space behind the plate. All cells in the fluid domain were initially air at 0.1 MPa which was modeled with an adiabatic, isentropic equation of state.

The symmetry plane was modeled as wall boundary conditions and the outer extents of the domain have free (non-reflecting) conditions. The pressure field within the shock tube was developed by mapping in the pressure field resulting from a 2-D simulation. There were a total of 8.8 million fluid cells in the fluid domain.

3.4. Complete DYSMAS model

The complete computational model containing the structure and fluid is shown in Fig. 6. In the model, the fluid and structure were coupled through the use of interface elements which define the “wetted surface” of the structure. In the model these surfaces were considered to be doubly wetted in which the fluid is considered to act on both sides of the shell elements. A mesh convergence study was conducted on both the structure and the fluid domain by beginning with a relatively coarse mesh and subsequently refining until a converged solution was obtained. The mesh presented in this paper represents the refinement level at which convergence occurred.

3.5 Computational shock front loading on the specimen

The DYSMAS simulation of the shock tube event allows for a visual observation of how the shock front interacts with and correspondingly loads the specimens. In the actual experiment the pressure transducers only provide a point wise time history at the inner wall. The interaction from the simulation of the shock front and specimen for the zero degree incidence simulation is shown in Fig. 7. In this figure, time zero is taken as the arrival of the shock front at the specimen. From this figure it can be observed that although the inner radius of the tube is 19.05 mm the shock wave actually interacts with the specimen over a larger area. This is due to the specimen deformation and partial venting of the gas into the atmosphere.

3.6. Computational Model Correlation

The shock loading conditions at the specimen were established using a two-step modeling approach. In the first stage an axisymmetric 2-D Euler domain was developed with a much more refined mesh than the full 3-D grid. This model contains the X-Z plane as shown in Fig. 8. In this 2-D model a much more refined grid was used to ensure that the shock front develops correctly at the muzzle end of the tube and minimizes shock front distortion due to larger cell sizes. This model contains a region of high pressure air, ambient pressure air, and a region of blocked cells representing the shock tube wall, which GEMINI treats as a rigid material. In the 2-D simulation, the specimen was omitted from the calculation as the goal was to establish a pressure field in the model that is equivalent to the pressure field that was measured during an experiment which was conducted with no plate. Several iterations of this model were run in which the magnitude and length of the high pressure region in Fig. 8 were varied. For each iteration, the pressure profile measured at the end of the shock tube in the simulation was compared to a measurement taken during the test. The pressure correlation with no specimen is shown in Fig. 9. Once the pressure profile in both the experiment and simulation were equivalent, the model was considered representative of the experiment with no specimen and was suitable for mapping into the fully coupled model. During the 2-D simulation, restart files were written during the propagation of the wave down the shock tube. By choosing a restart file just before the arrival of the shock front at the plate it is possible to use this file as a starting point in the full 3-D fluid domain which includes the panels. The axisymmetric pressure field in the 2-D simulation just before the shock front arrives at the specimen location was then mapped into the 3-D full-field fluid grid (Fig. 10).

4. Results and Discussion

The results obtained from the controlled experiments and their comparisons with the numerical simulations are presented below.

4.1. Pressure profiles

The typical pressure profiles, for all the incident angles of shock, obtained from the high frequency pressure transducer mounted on the muzzle that is nearest to the specimen are shown in Fig. 11. The incident pressure was 0.5 MPa for all the incident angles. The reflection of the shock wave in the case of 0° angle of incidence is a simple reflection. However, in the case of 15° and 30° angles of incidence, the oblique shock wave reflection can be either a regular or irregular reflection depending on the incident shock Mach number. However, in the present study, the shock Mach number was 2.6 (880 m/s) creating a “regular reflection” [19]. It is a well-known fact that the reflected oblique shock wave is of arc shaped and directs away from the reflecting surface as shown in Fig. 12. Since the pressure data were recorded at the muzzle section, the reflection pressures for 15° and 30° angles of incidence could not provide the complete nature of reflections as opposed to the case of 0° angle of incidence. Only a part of reflection pressure was measured for 15° angle of incidence and very small reflection pressure was recorded as the angle of incidence increased to 30° . However, both these reflection pressures could not be considered as the reflecting pressures acting on the specimen surface. In general, the reflection pressure varies as a function of angle of incidence with maximum value at 0° incidence and minimum at 90° incidence. Although the recorded reflected pressure does not indicate the true reflection pressure experienced by the specimen, it can be expected that the shock intensity was higher for 0° incidence and lower for 30° incidence with an intermediate value for 15° case.

4.2. Real-time deformation and DIC analysis

The real-time side-view deformation images of the specimen subjected to shock wave with 0° , 15° and 30° angles of incidence are shown in Fig. 13. The first image of each set corresponds to the beginning of the event and the last image to the maximum deflection. These side-view images were later used to validate the DIC results for the experiments with 15° and 30° angles of incidence. The side-view images were processed in MATLAB and the mid-point deflections of the vertical edge were obtained. The back-face stereo images of the speckled specimen obtained from high-speed cameras were analyzed using commercially available Vic-3D™ Digital Image Correlation software and the out-of-plane deflections of mid-point of the same side were obtained. Fig. 14 shows the comparison of the deflections obtained from DIC technique and those from side-view image processing for the case of 30° angle of incidence. It can be observed that there is a good agreement between these deflections. Hence, it can be concluded that the DIC technique works well even for the inclined targets.

With the good correlation between 3D DIC and side-view based outputs for the inclined targets, full-field deformations of the specimen were obtained using the DIC technique. The full-field out-of-plane deflection contours of the specimen, for every 0.5 ms until 2.5 ms, for all the cases of angle of incidence are shown in Fig. 15. For all the cases, the contour limits were chosen from 0 to 4.5 mm with 16 levels in between them.

The out-of-plane deflection contours in Fig. 15 show symmetry about the horizontal center line of the specimen in all the cases indicating symmetric bending of the specimen. For a better comparison, the midpoint out-of-plane deflections were plotted separately as shown in Fig. 16.

Clearly, the midpoint out-of-plane deflection increases with the decrease in angle of incidence. In all the cases the deflection reaches a maximum transient value after which the specimen undergoes elastic oscillations. These vibrations are of mode I nature. The maximum transient deflection is an important factor to consider when sensitive components are placed near the structures subjected to shock loads.

This out-of-plane deformation of the plate can be explained by considering the mobility of dislocations under dynamic plastic loadings. Under dynamic loading conditions, complete plasticity is not fully achieved as dynamic drag forces resist the dislocation movement. These drag forces are proportional to the dynamic motion of dislocation but in opposite direction. The drag force increases as the dislocation moves and by the time the deformation reaches the maximum transient value, the drag force reaches its maximum value and suppresses further motion of the dislocations. But due to high inertia, the dislocation again starts moving forward and consequently the drag force again increases. This process continues leading to elastic oscillations that decay with time leaving a residual plastic deformation in the specimen.

4.3. Deformation initiation and evolution

For normal shocks, the incident shock wave makes uniform contact with the specimen and gets reflected. However, in the case of oblique shocks, the incident shock wave first makes contact with the edge nearer to the muzzle. As shown in Fig. 12, the reflection starts from the edge which encounters the shock incidence first. Hence, it can be expected that the specimen deformation initiates from the edge nearer to the muzzle.

A careful examination of 3D DIC contours corroborated the sequence of deflection. The out-of-plane deflection contours of specimens subjected to oblique shocks are shown in Fig. 17.

It should be noted here that the left side of the specimen was nearer to the shock tube muzzle during experiments. From these contours it can be observed that the specimen deformed from left to right under the action of oblique shocks. Additionally it was observed that the out-of-plane deflection was lesser on the right side of the specimen compared to that on the left side, though the difference is quite less (about 0.3 mm). This decrease in the deflection can be attributed to the attenuation of shock wave due to the larger free space on the right side. On the whole, it can be concluded that the out-of-plane deflection of the specimens subjected to oblique shocks initiated from the side nearer to the muzzle and progressed towards the other side.

4.4. Finite Element Simulation Results

The main purpose of the numerical model is to investigate the effect of different angles of incidence on the deformation behavior of Hastelloy[®] X plate. The numerical model was first used to measure the specimen deflections for the angles of incidence of 0°, 15° and 30°. Then further investigation was carried out to study the deformation behavior of the specimen at other angles of incidence (45° and 60°) and at an additional shock wave incident pressure.

A comparison of the pressure history measured during the experiment and simulation for the 0° incident case is shown in Fig. 18. These pressure profiles are those which were measured by the transducer closest to the muzzle exit. It can be observed that the simulation is able to accurately model the incident and reflected pressure loading.

The displacement data that was captured during the experiments is used as a basis to correlate and validate the finite element model results. The quality of the correlation between the test data and numerical results in this study is quantified using the Russell Comprehensive Error measurement. The Russell error technique is one method which evaluates the differences in two

transient data sets by quantifying the variation in magnitude and phase. The magnitude and phase error are then combined into a single error measure, the comprehensive error factor. The full derivation of the error measure is provided by Russell [20] with the phase, magnitude, and comprehensive error measures respectively given as:

$$RP = \frac{1}{\pi} \cos^{-1} \left(\left(\sum c_i \sum m_i \right) / \sqrt{\sum c_i^2 \sum m_i^2} \right)$$

$$RM = \text{sign}(m) \log_{10} (1 + |m|)$$

$$\text{where } m = \left(\sum c_i^2 - \sum m_i^2 \right) / \sqrt{\sum c_i^2 \sum m_i^2}$$

$$RC = \sqrt{\frac{\pi}{4} (RM^2 + RP^2)}$$

In the above equations c_i and m_i represent the simulated and experimentally measured responses respectively. Excellent, acceptable, and poor correlation using the Russell error measure is given as: Excellent - $RC \leq 0.15$, Acceptable - $0.15 < RC \leq 0.28$, and Poor $RC > 0.28$. These criteria levels were based on a study that was undertaken to determine the correlation opinions of a team in support of a ship shock trial. The details of the process used to determine the criteria were presented by Russell [21].

Time histories were extracted from the DIC data at the center point of the specimen for all experiments that were conducted (0, 15 and 30 degree incidence). The midpoint out-of-plane deflections obtained from simulation were compared with those from experiments, shown in Fig. 19. A summary of the Russell error for all configurations for which test data is available is provided in Table 4. From these comparison plots of the experimental and simulation data it can be observed that there is a high level of correlation between the experimental results and the

computational simulations. It is noted here that the times of the simulation and experiments are arbitrary but are displayed using the simulation time. The two events are matched temporally by adjusting the experiment time until the first motions (deformation) of the center point align. The out-of-plane deflection comparison for all the experiments shows that the experiment and simulation results correlate well, although the simulation results do display a slightly more rapid recovery of the specimens that was observed in the experiments. Altogether, it can be concluded that there is a reasonably good agreement between experimental and numerical results, though the error is slightly increasing with the angle of incidence. Numerical simulations were continued for two more angles of incidence, 45° and 60° to investigate further the effect of angle of incidence.

4.5. Effect of incident angle

The intensity of reflecting pressure decreases with increase in the angle of incidence and the resultant deformations are expected to be lesser for shocks with high angle of incidence. The midpoint out-of-plane deflections of the specimen obtained from numerical model for different angles of incidence are shown in Fig. 20(a). It can be observed that the out-of-plane deflection decreases with increase in the angle of incidence. The midpoint of the plate moves only in out-of-plane direction (W) for 0° incident angle but there exist a horizontal displacement (U) for oblique shocked cases. The horizontal component of deformation tends to increase with increase in angle of incidence. The overall magnitude of deflection $\sqrt{U^2 + W^2}$ was plotted in Fig. 20(b) for different angles of incidence. The peak values of the magnitude of deflection and out-of-plane deflection as a function of incident angle is shown in Fig. 21. The increase in the horizontal component of displacement results in the increase in displacement magnitude. The

difference between out-of-plane displacement and the magnitude observed to be higher at higher angles of incidence and vanished at normal shock incidence.

4.6. Effect of incident pressure

Understanding the magnitude of change in transient plate deflections as a function of the incident pressure is of particular interest. Numerical analysis was carried out for a lower incident pressure with a magnitude of 0.25 MPa and the deflection data were obtained. The out-of-plane deflections are plotted in Fig. 22 for each angle of incidence. As expected, the deflections were found to be lower compared to those at high incident pressure (Fig.23). In this case, also, the out-of-plane deflection reduced as the angle of incidence increased. The existence of horizontal component of deformation and the deflection magnitude approachability with the decrease in the angle of incidence were similar as in the earlier case. The variation of “transient” peak out-of-plane deflection with respect to the incident pressure is shown in Fig. 24. The deflections in the specimen are largely governed by the impulse of the blast loading and the materials stress-strain characteristics at the respective strain rate. Since the impulse of the high pressure shock wave is almost double that of low pressure shock wave, the resulting deflections have a similar ratio. The plates possibly sustained more plasticity (and associated softening) under the higher loading which accounts for the more than doubling of the peak displacement. The deflection contours obtained from finite element analysis for the specimen subjected to shock wave having an incident pressure of 0.25 MPa with 30° angle of incidence are shown in Fig. 25. Shock tube muzzle was modeled nearer to the left edge of the specimen. From these contours it can be found that the deformation initiated from the side closer the muzzle and propagated to the other side as similarly reported in the experimental section for the high pressure case.

5. Conclusions

A series of experiments was carried out to understand the dynamic behavior of Hastelloy[®] X plates subjected to oblique shocks. A validated numerical analysis was also performed to further investigate the effect of angles of incidence and pressure on dynamic deformation. The main results are summarized below.

1. The out-of-plane deflection of the plates decreases as the angle of incidence is increased.
2. The reflected pressure and thus the energy imparted onto the specimen was observed to decrease as the angle of incidence increased.
3. The dynamic response of Hastelloy[®] X plates showed a “transient” maximum deflection followed by elastic oscillations that decay leaving a residual plastic deformation.
4. Normal shocks were found to produce larger plastic deformations.
5. For oblique shocked specimens, the deformation was observed to start on the edge nearer to the muzzle.
6. A shock wave with a lower incident pressure resulted in a reduction of the magnitudes of deflections but the overall behavior was found to be similar to that of a high pressure case.
7. The computational results were in excellent agreement with experimental findings.

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Table 1

Ni	Cr	Fe	Mo	Co	W	C	Mn	Si	B
47 ^a	22	18	9	1.5	0.6	0.1	1 [*]	1 [*]	0.008 [*]

^a As balance ^{*} Maximum

Table2

Density	8220 Kg/m ³
Melting range	1260 – 1355 °C
Elastic modulus	205 GPa (at 25 °C)
Yield stress	380 MPa (at 25 °C)

Table3

A	B	C	n	m	$\dot{\epsilon}_0$
380 MPa	1200 MPa	0.012	0.55	2.5	0.01 s ⁻¹

Table4

Angle of incidence	Magnitude error	Phase error	Comprehensive error
0°	0.031	0.019	0.032
15°	0.010	0.024	0.023
30°	0.097	0.074	0.108

Figure 1 (1.5 column fitting)

Figure 2 (2 column fitting)

(a)

(b)

Figure3 (1 column fitting)

Figure4 (1.5 column fitting)

Figure 5 (1.5 column fitting)

Figure 6 (2 column fitting)

Figure 7 (1.5 column fitting)

Figure 8 (2 column fitting)

Figure 9 (1 column fitting)

Figure 10 (2 column fitting)

Figure 11 (1 column fitting)

Figure 12 (1 column fitting)

Figure 13 (2 column fitting)

Figure 14 (1 column fitting)

Figure 15 (2 column fitting)

Figure 16 (1 column fitting)

Figure 17 (2 column fitting)

Figure 18 (1 column fitting)

Figure 19 (1 column fitting)

Figure 20 (2 column fitting)

(a)

(b)

Figure 21 (1 column fitting)

Figure 22 (1 column fitting)

Figure 23 (1 column fitting)

Figure 24 (1 column fitting)

Figure 25 (2 column fitting)