

**BALLISTIC IMPACT OF DEFORMABLE
PROJECTILES ON THIN DUCTILE TARGETS**

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BALLISTIC IMPACT OF DEFORMABLE PROJECTILES ON THIN DUCTILE TARGETS

By

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CERTIFICATE

This is to certify that the thesis entitled **Ballistic Impact of Deformable Projectiles on Thin Ductile Targets** by Vijeesh Vijayan has been prepared under our supervision and has attained a standard required for a PhD degree of the institute. The thesis is a record of bonafide research carried out by him and its contents have not been submitted to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

The effect of projectile deformation on target behaviour after ballistic impact was studied using aluminium projectiles and plates at low impact velocities. The effect of projectile parameters and target parameters on large deformation and damage on both projectile and target, the perforation efficiency of the projectile and the target resistance were studied experimentally and numerically. The capability of thin targets to induce a very short lived dwell phase on the projectile before undergoing damage during low sub-ordnance velocity impacts, the effect of deformation of pointed projectiles on failure behaviour of thin targets, and the effect of different projectile and target parameters on the ballistic response of both projectile and target were studied.

Projectiles made from Al6063-T6 (Al0.7Mg0.4Si) rod stock were impacted on targets with a circular span of 206mm cut from strain hardened Al 1100 (Al0.12Cu1Si) sheets of different degrees of hardness. Projectiles were launched from a compressed air operated smooth bore gun. Initial experiments were conducted by impacting 2.5mm thick targets with conical, 50% truncated and blunt projectiles of diameter 19mm to understand the mode and extent of deformation and damage that could occur in both the projectile and the target. The conical projectiles were found to undergo tip flattening while truncated projectiles showed no visible nose deformation. The blunt projectiles exhibited very little deformation, and the outward flow of the material at the contact interface was very less. Tip flattening of the projectile and radial cracking of the target motivated further experiments. Damage and energy transfer, and the associated changes in projectile kinematics were studied by varying apex angle and degree of nose truncation as projectile variables, and target thickness, obliquity and layering as target variables using projectiles of diameter 15.6 ± 0.1 mm ensuring a satisfactory degree of normality. Experiments were done on 2.5mm thick monolithic targets to study the effect of projectile nose apex angle and nose truncation. The effect of target thickness, target obliquity and layering were studied using cylindrico-conical projectiles with apex angle 34° . Plates of thickness 2mm, 2.5mm, 3mm, 4mm and 5mm were used to study the effect of target thickness.

While blunt cylindrical projectiles perforated the target by ejecting a plug slightly larger in diameter than the projectile itself, pointed cylindrico-conical projectiles underwent tip flattening and the newly formed blunt nose caused shear at the impact side and induced tensile stretching on the target at the distal side. The conical region of the projectile imparted local necking followed by tearing and subsequent bending. The 50% truncated projectiles caused shear and further thinning which seemed to be insufficient to cause prominent tearing. This was followed by bending. Global stretching was more for targets hit by purely blunt projectiles where as most of the damage was concentrated near the contact region for the other two cases.

The effect of apex angle was studied by impacting cylindrico-conical projectiles of apex angles 22.5° , 34° , 45° , 66.5° and 90° on targets of thickness 2.5mm. The projectiles of apex angles 22.5° , 34° and 45° underwent considerable tip flattening. The newly formed blunt nose caused shear deformation in the impact side and stretching on the distal side, and caused a plug to be separated from the target. The conical region of the projectile imparted local necking followed by tearing and subsequent bending. The tip of projectiles with apex angles 66.5° and 90° became slightly rounded after impact. A distinct change in failure mode was observed in case of targets hit by projectiles of apex angles 66.5° and 90° and this was seen to affect the efficiency of the penetrator. Plug diameter, reduction in projectile length, length of radial crack, maximum number of petals and maximum deflection for any velocity were found to depend on apex angle, in the considered velocity range. The dependence of crack length on slant height of the cone was evaluated. Comparison of perforation efficiency of the projectiles was made and the trend was established. The possible reasons for the observed trend and the effect of change in failure behaviour on perforation characteristics were studied.

The effect of nose truncation of conical nosed projectiles with apex angle 34° was studied using 25%, 50% and 75% truncations, keeping the mass constant. The tip of all the truncated projectiles remained stable irrespective of velocities. The flat end of the truncated projectile immediately comes into contact with the target surface unlike the newly formed flat end of the pointed projectile where some time is elapsed in attainment of tip-stability. The minimum truncation for stable nose seems to be governed by the maximum deformation of a non-truncated nose of the same included angle impacting a target of a given thickness or strength. Thus nose stability would be

a function of apex angle, target thickness and strength subjected to constraints imposed by transitions in failure mechanisms/terminal behaviour. Truncated projectiles caused ejection of a plug. Plug diameter and plug thickness at the center and the failure zone were measured. Quantitative and qualitative aspects of radial cracking were found to depend on the percentage of truncation. The perforation characteristics of truncated projectiles were studied and compared with non-truncated conical projectile.

Almost all targets caused projectile flattening and exhibited failure by initial plug ejection and subsequent petal formation. The plug diameter and hence the flattened tip diameter of the projectile increased with target thickness. However targets of 5mm thickness did not cause tip flattening and ejection of plug. The nose transformed into a parabolic or ogival shape. The conical projectiles required more energy to perforate thicker targets. However, the resistance offered by 5mm and 4mm targets seems to be comparable. The perforation efficiency does depend on the energy expended in the initial stages of deformation. The strength of the target was found to influence the deformation characteristic of the projectile. The possible implications on perforation characteristics have been discussed.

The targets were impacted at inclinations of 30° , 45° and 60° with respect to the vertical plane (the plate normal being inclined at the same angles with respect to the barrel axis). The projectile underwent tip separation and bending. In several cases the plug was found attached to the projectile. The failure behaviour of the target was characterized. Target obliquity improved target resistance to perforation and also reduced possibilities of damages due to free flying plugs. A few experiments were done to study the effect of thickness. A transition in failure mode and the ballistic properties was observed.

Layered configurations equivalent to 3mm monolithic targets consisting of two 1.5mm targets, and 1mm and 2mm targets in either orders, layered configuration consisting of two 2mm targets equivalent to 4mm monolithic targets and layered configurations consisting of 2 and 3mm targets equivalent to 5mm monolithic targets in either orders (ie., 2/3 and 3/2) were impacted with conical projectiles with apex angle 34° . The effect of order of the plates and the target strength on the mode of projectile deformation and the contribution of the plate receiving impact was studied. The differences in failure behaviour of the first and second plates in each case were observed. In some cases a single plug with a polished distal side and textured impact

side or, polished impact side and unpolished distal side was recovered. In other cases the plugs were ejected from both the plates. A dome shaped plug having a polished distal side was found fused with the tip of the projectile in a certain case. Contrary to the absence of tip flattening in case of monolithic targets of 5mm thickness, it was observed that projectile deformation led to plug ejection in equivalent layered case. The comparison of ballistic properties between 3mm monoliths and equivalent layered combinations were made.

The finite element models of the projectiles and plates were created and interaction was defined between the components in the commercial solver ABAQUS/Explicit to numerically simulate the impact events. The material definitions and meshing was found to be important in capturing the phenomenon successfully. Models with axisymmetric quadratic and 3-D hexahedral elements with hourglass control were employed in the study. Axisymmetric models allowed reasonably large number of elements across thickness. Increasing the number of elements across thickness by maintaining unit aspect ratio proved computationally expensive in solid models. Johnson-Cook (JC) constitutive and failure models as defined in the software were used to model the material. Some of the constants were determined through material tests. A few were either judiciously adapted from previously published results or reverse calibrated based on experimental observations. The material definition took care of damage initiation and evolution. Elements that failed were deleted from the model thereby simulating damage. A few check points were defined to validate the models against experimental observations. Presence or absence of projectile deformation and response of the target were recreated with reasonable satisfaction. The phenomenon of radial cracking and petalling were successfully captured by the solid models. The total artificial strain energy was found to be very less. Several transitions in experimental observations were successfully simulated. Nevertheless there is scope for further refinement of the models in terms of both material representation and mesh control.

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