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Impact characteristics of stiffened plates penetrated by sub-ordnance velocity projectiles

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Abstract

A series of experiments are carried out to explore the impact characteristics of stiffened plates struck by the sub-ordnance velocity projectiles. Considering the relative position of impact point to the nearest stiffeners on target, six kinds of representative target plates with different stiffened styles are specially designed. Altogether sixteen target plates, respectively without, single- and cross-stiffened are tested and compared. Two kinds of projectiles, one with spherical nose and the other with truncated oval nose, are fired using a 25 mm refitted cannon. The initial velocities of projectiles range from 244 to 430 m/s. Experimental results show that the penetration process is greatly dependent on the nose shapes of projectiles. The tumbling of truncated oval-nosed projectiles is very prominent, which results in the great uncertainty of deformation and failure mode of target plates. While the spherical-nosed projectiles keep much more stable, plugging and ductile hole enlargement are the most distinct failure modes. In the end, some empirical formulas aimed at blunt-nosed projectiles are proposed, which could be helpful for the design of the protection structures.

Keywords: Stiffened plate; Impact; Perforation; Empirical formulas

1. Introduction

Stiffened plates are the most often used structure in aircraft, ship and many civil structures due to their buckling efficiency in resisting both in-plane and out-of-plane loading. As their behavior under static load has been almost fully elaborated, its response when subjected to both uniform and localized blast loading conditions has been a topic of investigation widely reported in the literature over the past decade [1–7]. Before the mid-1980s, the work reported was almost concerned with unstiffened and stiffened plates which resulted in large inelastic deformation [1,2]. During the 1990s the investigations were extended to include work examining the effect of boundary conditions, plate stiffeners and loading conditions in the quest to identify, understand and predict both deformation and tearing [3–6]. Research works showed that for stiffened plates, stiffeners influence not only the displacement, but also the force transfer path. Compared with common flat plates, some different failure modes are also exhibited by the stiffened ones when subjected to intense blast loads.

Though much effort had been made on the dynamic behavior of stiffened plates under blast load, there are few works which can be found in the literature dealing with their impact behavior when struck by free-flying projectiles. As structural impact problems have become increasingly important for the modern industry, it is necessary to grasp the impact behavior of stiffened engineering structures. A typical example occurs in the design of offshore structures. Account is often taken on the accidental loads such as dropped objects, collisions, explosions and penetration by fragments. Most of these accidental loads are also pertinent for the design of protective structures in the process industry or fortification installations for defense purposes. Another example exists in commercial aircraft, as Hinrichsen [8] discussed the effects of in-flight damage to commercial transport aircraft caused by terrorist attacks. Currently, commercial aircrafts are not equipped with any countermeasures to defend against attacks. It becomes

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Nomenclature

SN, **TN**: Abbreviations for spherically and truncated oval-nosed projectiles, respectively
F, **SI**, **SI***, **ST**, **CS**, **QS**: Abbreviations for the names of different target plates (Table 1)
v_i, v_{50}: Initial velocity and ballistic limit of target plate
h_t: Thickness of the unstiffened plate or the base plate of target plate
h_E: Equivalent thickness of stiffened plate relative to the unstiffened plate with same material
$\overline{h}_E^V$, $\overline{h}_E^S$: Dimensionless equivalent thickness obtained from different equations
α: Incident angle of projectile
m_p: Mass of projectile
E_{drop}: Energy drop of projectile before and after perforation
d: Diameter of projectile

necessary to determine likely damage scenarios caused by these projectiles to enable the development of techniques for safely land the damaged aircraft.

Many investigations on structure impact problems are available in the open literature, as many of the works carried out by military and industrial research organizations have been classified. Comprehensive reviews on the researches into the penetration and perforation of structures by free-flying projectiles can be found in the journal papers by Goldsmith [9], Backman [10] and Corbett et al. [11], and in the books by Zukas [12,13]. Although many investigations have been presented over the years, most papers dealt with only unstiffened target plates with different thickness and material. Research works concerned with more complex-shaped target such as the stiffened plate are very limited due to their high complexity.

This paper aims at quantifying the damage of stiffened plates stuck by sub-ordnance velocity projectiles. As work in structure impact area has often been considered as experimental in nature, a series of specially designed experiments are carried out. The targets, projectiles and detailed experimental setup are reported in detail. Test results including track of projectile as well as deformation and damage mode of targets are discussed in the order of the target style. Some empirical formulas aimed at blunt-nosed projectiles are proposed based on test results, which could be very helpful for the design of the protection structures.

2. Experimental programs

2.1. Target plates and material

Considering the local characteristics of high-velocity impact phenomenon, the common practical stiffened structures can often be simplified into a planar stiffened target plate as shown in Fig. 1. It includes the base plate, transverse and longitudinal stiffeners. Imagine a free-flying projectile impact the target

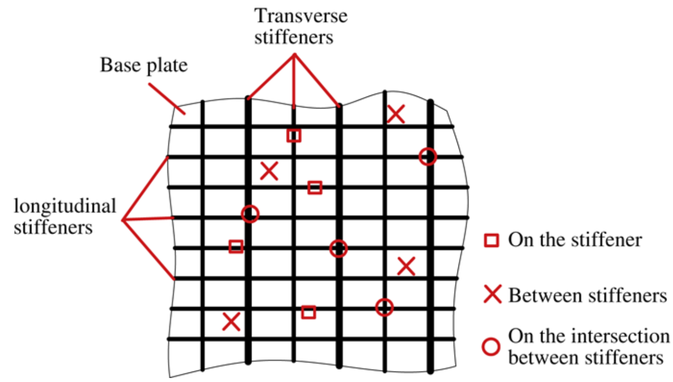

Fig. 1. Possible impact locations when stiffened plate is stricken by projectile.

plate, the impact point may be distributed at any location on the panel face with even probability. If we consider the relative position of impact point to the nearest stiffeners, some typical locations can be classified as follows:

Case **A**: During the perforation process, the impact point is just at mid-bay between two stiffeners and incident projectile penetrates only the base plate and does not touch any stiffener even if very close to them.

Case **B**: The impact point is just located at the midpoint of the panel where there is a stiffener (transverse or lengthwise). After the projectile perforates base plate, it wholly or partly perforates (breaks) the stiffener too.

Case **C**: Impact point is nicely located at the midpoint of the panel where two stiffeners intersect. After the projectile perforates base plate, it also wholly or partly perforates the two cross-stiffeners.

Though many different cases may occur, the study on the three cases above will help to identify the worst damage scenario for the prediction of the residual strength of damaged stiffened structures. Corresponding to the impact cases (Case A, B and C), several types of stiffened plates with different styles are designed and manufactured as targets. Each kind of target plate is so designed that it can represent one of the typical impact scenarios. As listed in Table 1, altogether six types of square target plates are tested, with four kinds of stiffened configurations. The global dimensions of all plates are 500 × 500 mm. The flat plate with thickness 5 mm and without any stiffener is named **F** target, which is designed as a comparative benchmark. All other target plates are respectively single-, cross-(**CS**) and quadric-(**QS**) stiffened. Thereinto, three subtypes are included in the single stiffened plates with different stiffener sections (**SI**, **ST** and **SI***). They are so named just according to their different stiffener section shape. The base plate thickness of all targets is 5 mm except **SI***, which is 10 mm in thickness. The stiffener section of all the stiffened plate is 5 × 25 mm rectangle except the **ST** plate, which is a single-stiffened plate with '**T**' sectioned stiffener (Table 1).

All target plates tested were manufactured from the same batch of 16MnR steel hot rolled plates with initial thickness 10 mm. Both base plates and stiffeners were cut and planed from these plates using special planer milling machine. After careful cutting from the larger plate, about 20 holes were