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REPLICA SCALE MODELLING OF LONG ROD TANK PENETRATORS

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Experiments and simulations have been conducted using scale size tungsten alloy penetrators at ordnance velocity against an oblique plate array consisting of an inert sandwich and a base armour. The penetrators are made from 2 types of tungsten alloy with different tensile strength. Two scale sizes have been used: scale size 1:6 using simple cylindrical rods and scale size 1:3 with a more realistic geometry including a threaded shaft section. The purpose of the experiments is to establish the difference in behaviour between the 2 types of penetrators and to assess the differences between the scale size 1:6, scale size 1:3 and full scale results. The purpose of the hydrocode simulations is to assess the influence on penetrator performance of the yaw angle of the penetrator prior to impact.

INTRODUCTION

The well-known competition between projectile and armour also includes tank ammunition and tank armour. Tank ammunition has to be improved constantly for this reason. This is not a luxury, as witnessed by tests against main battle tanks in both Germany and the United States [1, 2].

In order to assess the performance of improved long rod tank penetrators, full scale validation tests are essential. These full scale tests can not be performed in The Netherlands. The Netherlands co-operates with Switzerland, where full scale testing with tank ammunition is a competence. The Dutch contribution to this co-operation is the fully instrumented scale size testing of long rod tank penetrators, assisted by computer simulations of the phenomena during perforation and penetration of the complex plate array involved. Scale size testing enables us to assess the influence of parameter variations (such as projectile strength) on projectile performance at lower cost than full scale testing.

EXPERIMENTS

Penetrators and sabots

The geometry of the scale size penetrators is based on the exact scaling of both length and mass of the full scale long rod penetrator, because length and mass are considered to be the most important geometry-related properties determining the penetration capacity of a long rod penetrator. Inevitably, a compromise has to be made somewhere and in this case an equivalent rod diameter D_{eq} is calculated from the scaled length and the density of the penetrator material to satisfy the required scaled mass. The penetrators with scale size 1:6 are simply smooth cylindrical rods with diameter D_{eq}. The penetrators with scale size 1:3 (as well as the full scale rods) have a threaded section to transfer the acceleration forces from sabot to penetrator, a nose and tail diameter reduced relative to D_{eq} to satisfy the required scaled mass, and a spherical nose (full scale L/D = 30 with a 15° nose cone). Fig 1. shows the assembly of penetrator and sabot for scale size 1:6, Fig. 2 shows the assembly for scale size 1:3.

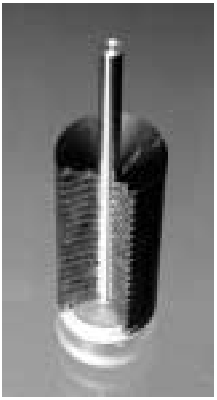

Figure 1: Assembly for scale size 1:6.

Figure 2: Assembly for scale size 1:3.

The replica scale penetrators were machined from full scale hammered tungsten alloy rods for tank ammunition (“rod design A” and “rod design B”). Two types of penetrators are involved: L/D = 20 penetrators and L/D = 30 penetrators, the latter are made from higher strength material. The full scale penetrators are similar to the rod designs A and B. Table 1 gives a number of properties of the replica scale and full scale penetrators.

Table 1: Penetrator properties

		Full scale	Scale size 1:3	Scale size 1:6
L/D = 20	Designation	MX520	rod design A	rod design A
	Deq x L	Ø26 x 520 mm	Ø8.22 x 170.7 mm	Ø4.11 x 85.3 mm
	Mass	4.6 kg	160.4 gram	20.05 gram
	UTS	1400 MPa	1400 MPa	1400 MPa
	ultimate strain	10 %	10 %	10 %
L/D = 30	Designation	MX660	rod design B	rod design B
	Deq x L	Ø22 x 660 mm	Ø7.81 x 226.7 mm	Ø3.91 x 113.3 mm
	Mass	4.6 kg	188.9 gram	23.61 gram
	UTS	1500 MPa	1700 MPa	1700 MPa
	ultimate strain	10 %	8 %	8 %

The penetrators with scale size 1:6 were launched with a 29 mm laboratory gun using a pusher-plate type 4-piece PVC sabot, see Fig. 1. The penetrators with scale size 1:3 were launched with a 78 mm laboratory gun using threaded 4-piece aluminium sabots designed and manufactured by SwRI (San Antonio, Texas, USA), see Fig. 2. The bore-riders are covered by 4-piece Nylatron shells (not shown in Fig. 2). A total of 40 scale size experiments have been conducted, 10 for each combination of scale size and penetrator type. The full scale penetrators were launched by a 120 mm tank gun in Thun (Switzerland) by GR/FS262 by Mr. W. Odermatt.

Target configuration and test set-up

Fig. 3 gives the plate array for the third scale experiments. This scale size plate array corresponds with the targets used for full scale testing in Switzerland (and of course the sixth scale experiments) and are representative for spaced armour protecting the frontal arc of main battle tanks.

The sandwich and base armour plates (both at 60° NATO) are spaced from one another using wooden spacers at a distance as large as possible from the intended point of impact, see Fig. 4. This figure also shows the foils for triggering the flash X-ray equipment to establish the penetrator orientation just before impact (vertical yaw on X-ray left in picture, horizontal yaw on X-ray lying in front of the sandwich) and to capture the penetrator between sandwich and base armour.

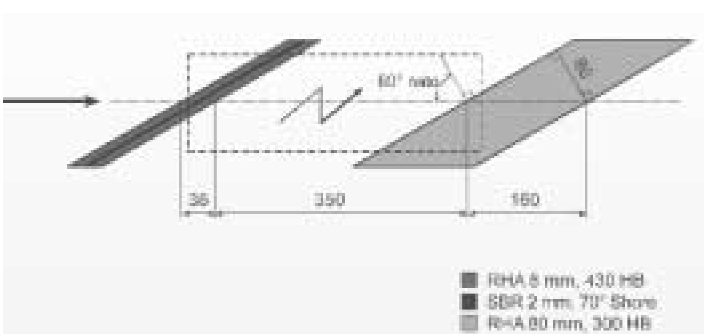

Figure 3: Plate array for scale size 1:3 experiments.

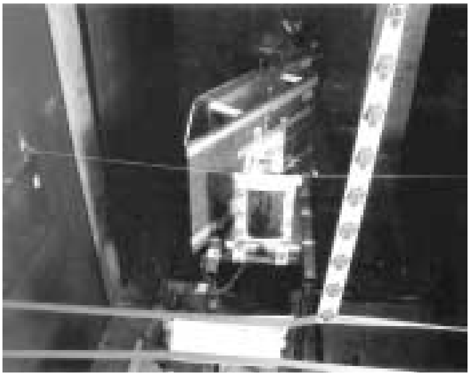

Figure 4: Plate array plus trigger foils for flash X-ray (scale size 1:3).

Experimental results

Fig. 5 through Fig. 8 show typical scale size results for the penetrator between the perforated sandwich armour and the yet to be penetrated base armour. The scale size 1:6 experiments show the L/D = 20 penetrator to break its nose whereas the L/D = 30 penetrator, made from higher strength material, remains intact but takes a curved shape. The scale size 1:3 experiments show multiple fractures in both types of penetrators, and again the front part of the L/D = 20 penetrator gets fully separated from the rest of the rod.

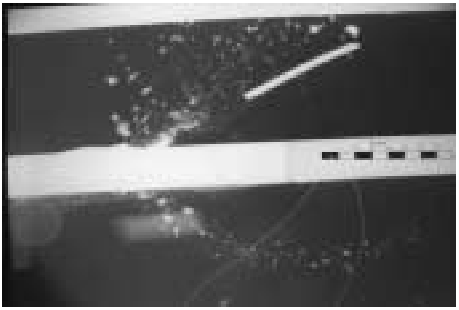

Figure 5: Scale size 1:6, L/D = 20.

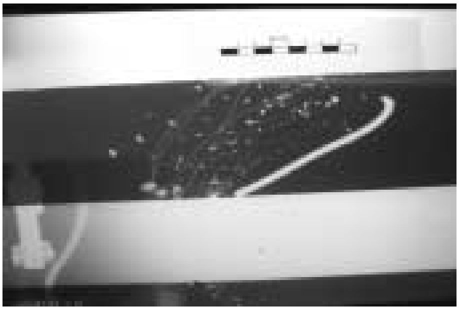

Figure 6: Scale size 1:6, L/D = 30.

Figure 7: Scale size 1:3, L/D = 20.

Figure 8: Scale size 1:3, L/D = 30.

Fig. 9 and Fig 10. show typical radiographs from full scale experiments with L/D = 20 and L/D = 30 penetrators. These figures resemble the radiographs of the scale size 1:3 experiments (Fig. 7 and Fig. 8).

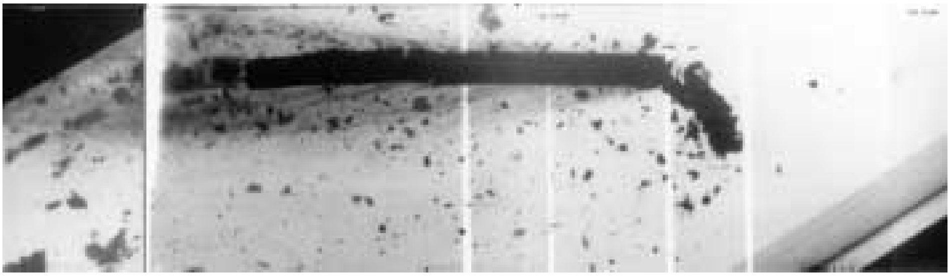

Figure 9: Full scale, L/D = 20 (Source: GR/FS264, Thun, Switzerland).

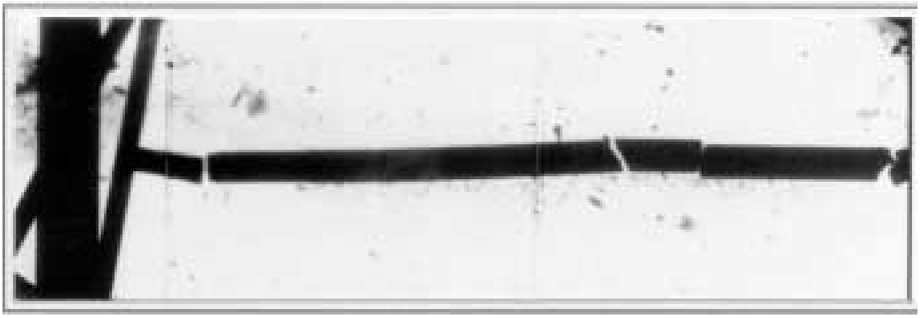

Figure 10: Full scale, L/D = 30 (Source: GR/FS264, Thun, Switzerland).

Table 2 summarises the experimental results as average % DOP (Depth Of Penetration) into the base armour. A DOP of 100% means complete penetration of the base armour. The velocities given in Table 2 are the average impact velocities of the concerning experiments.

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Table 2: Average DOP as % of the nominal base armour thickness

scale size	L/D = 20	L/D = 30
1:6	50%, 1767 m/s	57%, 1744 m/s
1:3	43%, 1798 m/s	36%, 1667 m/s
full scale	90%, 1635 m/s	100%, 1650 m/s

The average DOP of the third scale penetrators is smaller than for the sixth scale penetrators and the L/D = 30 penetrators perform worse instead of better than the L/D = 20 penetrators for the third scale experiments. This is caused by the breaking behaviour of the threaded penetrators used for the third scale experiments, see Fig. 7 and Fig. 8. This breaking behaviour is different for the L/D = 20 and L/D = 30 penetrators, partly explaining the poor performance of the third scale L/D = 30 penetrators. Also the lower average velocity of the third scale L/D = 30 penetrators (1667 m/s) compared with the L/D = 20 penetrators (1798 m/s) partly explains the low average DOP of L/D = 30 (36%) compared with L/D = 20 (43%).

The DOP of the full scale experiments are well above the scale size results. The L/D = 20 or MX520 full scale rod has no chance to perforate the base armour at 1635 m/s. The L/D = 30 or MX660 full scale rod perforated the target in spite of breaking after the sandwich armour.

One of the original goals of this research was to investigate how well scale size results compare with full scale results. Unfortunately, the scale size results themselves (1:6 and 1:3) cannot be compared. Apart from the divergence between these scale size results, non-scaling effects originating from not satisfying the replica model law are unavoidable, hence making a perfect direct comparison between scale size and full scale results impossible. These non-scaling effects (especially fracture toughness and time, see [3]) are aggravated by using a complex plate array which results in breaking up of the penetrator between sandwich armour and base armour. Nevertheless, the scale size 1:3 experiments for both types of penetrators yield radiographs between sandwich armour and base armour corresponding with the full scale experiments. Replica scale modelling is useful in investigating tendencies or in making comparisons, but validation by full scale results is essential.

SIMULATIONS

Modelling

The simulations performed for this project ran on a Unix machine and used Auto-dyn-3D version 3.0.07 up to and including 3.0.12.

For the penetrators the material ‘tungsten alloy’ from the Autodyn material library (Johnson-Cook) has been chosen, using a shock equation of state. For armour steel the material ‘4340 steel’ from the Autodyn material library (Johnson-Cook) has been chosen, using a linear equation of state (a shock equation of state was not available for 4340 steel in Autodyn version 3.0). The material parameters for tungsten alloy and 4340 steel are changed according to the known material parameters available (density, tensile strength and ultimate strain). For the rubber sheet of the sandwich armour the library material ‘polyrubber’ (Synthetics) was used. This material uses a hydrodynamic constitutive equation and has a shock equation of state. A sensitivity-analysis learned that for the model in question it was not important which type of rubber was used as long as the density of the material was correct (namely 1 g/cm^3).

The simulations for scale size 1:6 used ‘Pmin’ (hydrodynamic tensile limit) as failure criterion for both the penetrator and the sandwich armour. The later simulations for scale size 1:3 (not included in this paper) used ‘principal stress/strain’ instead of ‘Pmin’ as failure criterion for the perforation of the sandwich armour, because this is physically more correct. During the final stage of penetration of the residual penetrator into the thick base armour the failure criterion was set to ‘none’ for both the penetrator and the armour because this is known to give the best agreement with experiments for a projectile not perforating the armour. Also for the rubber sheet of the sandwich armour the failure criterion was ‘none’.

In all cases an erosion strain of 1.5 was used for the tungsten alloy penetrator and an erosion strain of 2.5 was used for all steel armour plates. For the rubber sheet of the sandwich armour an erosion strain of 6 was used.

Simulation results

The intention of the scale size 1:6 simulations was to assess the DOP to be expected from the L/D = 20 and L/D = 30 penetrators as a function of the yaw angles. For all simulations the same impact velocity of 1750 m/s was chosen. Fig. 11 gives the simulated L/D = 30 penetrator between sandwich armour and base armour for the zero yaw situation.

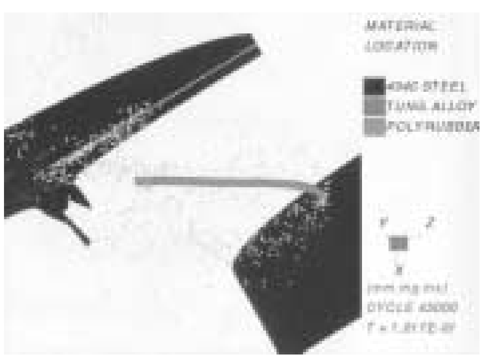

Figure 11: L/D = 30 penetrator between sandwich armour and base armour for zero yaw (scale size 1:6).

The various simulations indicate that the influence of projectile orientation is most apparent if the penetrator has a (horizontal) yaw corresponding with an inclination away from the oblique target (-2° yaw, see Fig. 12). In this case the two types of penetrators behave differently. The residual L/D = 20 penetrator after perforation of the sandwich is still a more or less straight rod of which the nose has broken off. Due to the initial yaw, the rod will be inclined even further away from the base armour during penetration (top of Fig. 12). In contrast, the L/D = 30 penetrator will have a bent nose after perforation of the sandwich armour which leads to a rotation of the penetrator during penetration of the base armour compensating for the initial yaw (bottom of Fig. 12). This results in a *higher* depth of penetration than for an originally unyawed L/D = 30 penetrator (middle of Fig. 12).

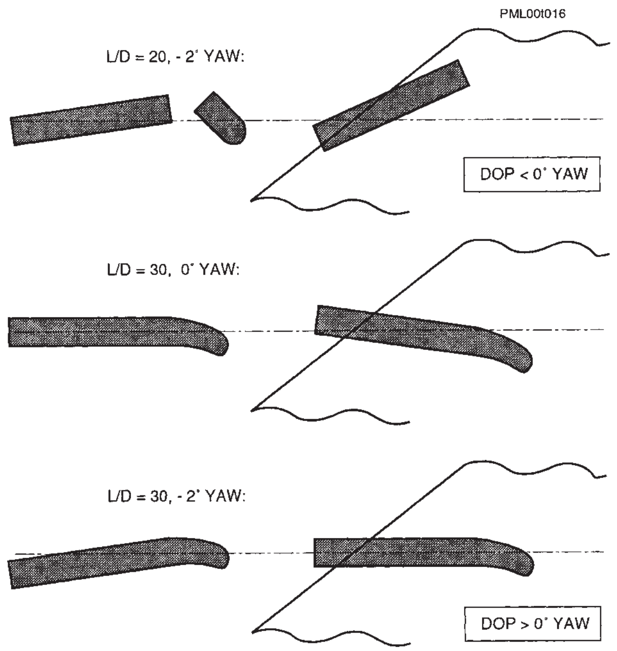

Figure 12: Penetrator behaviour after perforation of the sandwich armour, according to the simulations (scale size 1:6).

CONCLUSIONS

Both the scale size 1:6 and 1:3 experiments show the large effect that the inert sandwich armour has on the residual penetrator performance against the base amour of the oblique plate array used for this research. This performance degradation is achieved by breaking and bending as well as rotation of the penetrator prior to impact onto the base armour. These phenomena level out differences in performance between the L/D = 20 and the L/D = 30 penetrators. Nevertheless, the scale size 1:3 experiments for both types of penetrators yield radiographs between sandwich armour and base armour corresponding with the full scale experiments.

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According to the scale size 1:6 computer simulations, the influence of projectile orientation is most apparent if the penetrator has a (horizontal) yaw corresponding with an inclination away from the oblique target. In this case the two types of penetrators behave differently: the L/D = 20 penetrator achieves a smaller average DOP whereas the L/D = 30 penetrator achieves a higher average DOP than for the zero yaw situation.

Due to the divergence between the scale size results and due to non-scaling effects originating from not satisfying the replica model law, the scale size 1:6 and scale size 1:3 results cannot be compared and neither can the scale size and full scale results be compared. Replica scale modelling is useful in investigating tendencies or in making comparisons, but validation by full scale results is essential.

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