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THE EFFECT OF CRACKS ON THE BALLISTIC PERFORMANCE OF CONTOURED PROTECTIVE BODY ARMOUR PLATES

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This work determined the effects of batch to batch variation, deterioration due to age and induced cracking on the ballistic performance of contoured protective body armour plates. Cracks were introduced into batches of plates, X-rays were then used to determine the positions of cracks and the ballistic performance of these cracked areas evaluated. A statistical analysis of all results was performed in order to assess the V_{50} velocity and the velocity at which the failure probability was less than 5% (V_{05}).

It was found that all batches of plates assessed as A1 condition exceeded the ballistic specification by at least 15% and even when severely cracked the ballistic performance remained at least 10% above specification. No evidence was found of any construction effects, defects or deterioration due to age that resulted in a reduction in ballistic performance.

INTRODUCTION

The aim of the research was to determine the degree of variability in the ballistic performance of six production batches of contoured protective body armour plates classified as being in A1 condition. Crack damage was induced into a selection of production plates from the six batches and any change in performance against the UK/SC/4898[1] specification was determined and compared with the performance of undamaged plates. The ballistic trial evaluated the performance of the plates against 7.62mm x 51mm ammunition. To compare the performance of the plates accurately, the condition of the plates was verified by X-ray before and after damage was induced. One batch of rejected plates with clearly visible damage was also evaluated.

V_{50} EVALUATION OF THE BALLISTIC PERFORMANCE OF CERAMIC ARMOUR PLATES

The UK/SC/4898[1] specification is a proof test to confirm that the plates stop the designated ammunition at a specified velocity. However, to evaluate the performance of one plate against another, a V_{50} method is normally used where the velocity at which the plates are perforated is determined. A V_{50} is defined as the velocity at which, with the specified projectile and target material the estimated probability of penetration is 0.5 [2]. The UK/SC/5449[3] specification defines the range (spread) of velocities allowed for a six shot V_{50} as $40ms^{-1}$. This spread is bracketed by the lowest recorded velocity for a penetration and the highest velocity recorded for a stop. In this trial three V_{50} ballistic tests were carried out on each of six different batches of plates, representing 12 years of production. All the V_{50} tests in the trial were against plates supported by CBA soft body armour which was strapped onto a conditioned Plastilina® backing with one shot aimed at the centre of each plate tested, figure 1.

Figure 1: Typical test setup

RESULTS OF V_{50} TRIAL ON A1 CONDITION PLATES

The results for all six batches of A1 plates tested showed that following the test methodology for calculating V_{50} described in Annex B of the UK/SC/5449[2] specification all of the A1 condition plates exceeded the specified velocity range. Figure 2 illustrates that the performance of these batches was 16% to 24% above the limit specified.

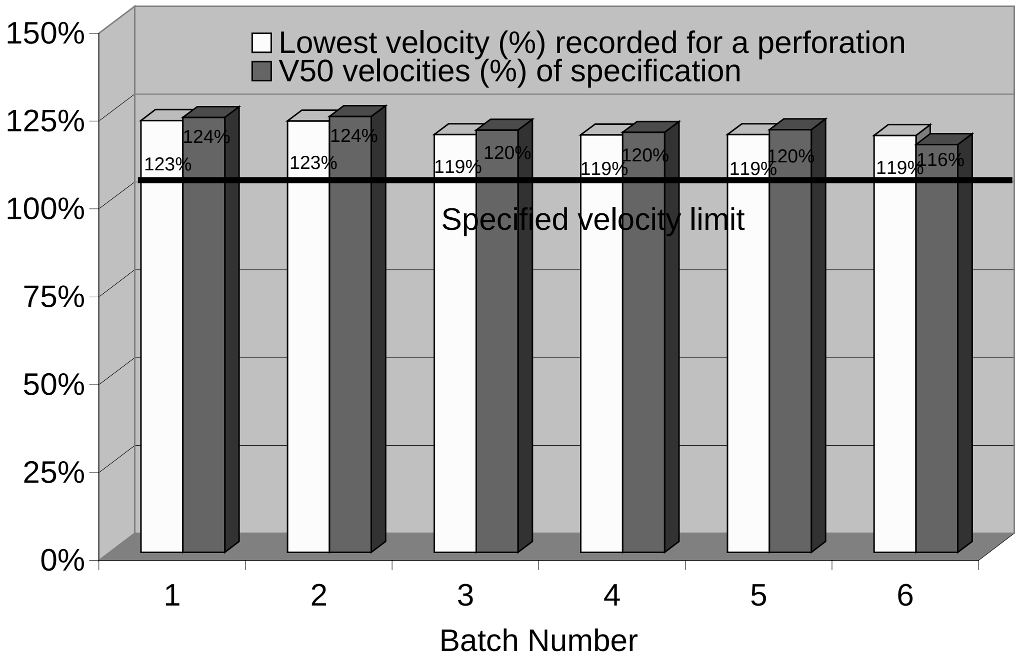

Figure 2. Comparison of V_{50} velocity for all batches of plates in A1 condition against specified proof test velocity limit (%) and lowest velocity recorded for perforation for each batch type (%)

RESULTS OF V_{50} TRIAL ON PRE-CRACKED CONDITION PLATES

To study the effect of cracks a number of A1 plates from the most recent production years (batches 1 and 2) were ‘cracked’ in a hydraulic press. Sufficient load was applied until the plate cracked a distinct noise indicated this happening. After this operation they were checked visually and there were no clear signs of damage seen at the surface.

These plates were then X-rayed to show the positions of the cracks. The X- rays of these plates showed definite cracking in all cases, a typical example of an armour plate showing induced cracks and the aiming point (shot position) is shown in figure 3. The X-ray’s were scaled 1:1 with the plates so that the X-rays could be used as a template to transfer the pattern of the cracks and mark up each of the test plates, an example is shown in figure 4. Three V_{50} ballistic trials were performed on these pre-cracked plates with the shot being aimed at the area of the plate with the most cracks.

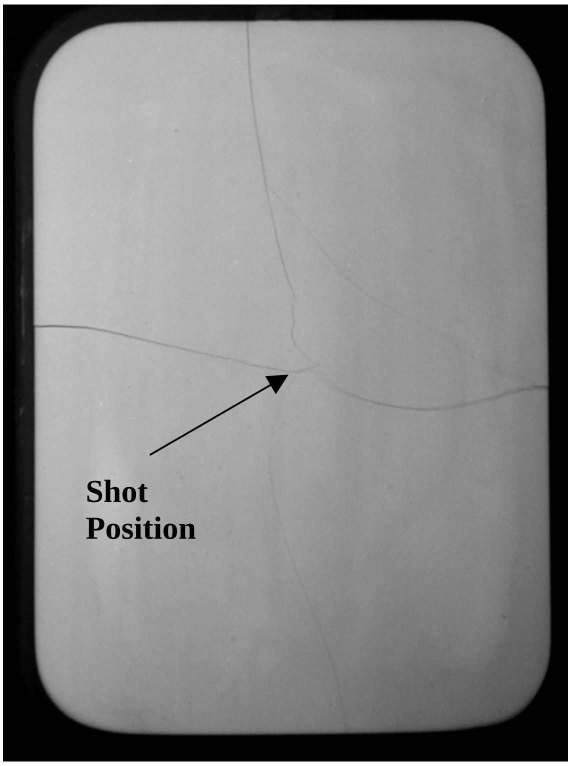

Figure 3.
X rayed Armour plate showing induced cracks and shot position

Figure 4.
Typical cracked plate (after test) showing transfer pattern of crack markings and shot aiming position

After this trial, batches of plates from earlier production years were X-rayed before V_{50} ballistic testing to confirm their condition. Most of plates classified as A1 from these batches showed no evidence of cracks. However the X- ray examination confirmed that a small proportion of the oldest plates (batches 5 and 6) had some very fine cracks which were difficult to detect when visually inspected These plates were separated from A1 condition plates and a V_{50} obtained for each, see batches 5 & 6 in table 1.

The results showed that plates with fine cracks still performed 10-12% above the specification, but had a 4-10% reduction in V_{50} when compared to A1 condition. Pre-Cracked plates performed 15% above the specification with a 7-8% reduction in the mean V_{50} performance of each batch of pre-cracked plates compared with A1 condition. The damaged areas of a plate batch that had been classified as rejects and exhibited clearly visible damage were also tested. These plates also performed 12% above the specified performance level. A statistical analysis of all the plates in the trial was carried out on the data, to enable the prediction of levels of confidence, based on the variability in performance against perforation and variations due to batch type.

Table 1 Effect of cracking on V_{50} trial results

Batch number	Plate Condition	Performance above specification (%)	% change in mean V_{50} ms^{-1} A1 compared with cracked
1	A1	24%	
	'pre-cracked'	15%	-7.2%
2	A1	24%	
	'pre-cracked'	15%	-7.7%
5	A1	20%	
	cracks detected by X-ray	10%	-8.5%
6	A1	16%	
	cracks detected by X-ray	12%	-3.9%
Reject plates	Damage clearly visible	12%	

THEORETICAL STATISTICAL MODEL OF PLATE DATA

A statistical approach was used to model the behaviour of the plates and to provide statistically reliable data on the V_{50} and proof velocity. The analysis used the standard statistical method of a generalized linear model with binomial errors and logit link function (also referred to as logistic regression). This allows probabilities to be predicted as a function of a set of input variables. Fieller's method can then be used to estimate, and produce a confidence interval for the V_{50}, V_{05} and V_{95} [4,5,6]
Figure 5 shows a graphical representation of the probability of penetration as a function of normalised velocity for all the batches, with the normalised specified velocity limit equal to 1. It was found that the statistical model of plate performance gave a graphical output comparable to the Critical Perforation Analysis (CPA) proposed by Gotts *et al* [7]

This data was tabulated in table 2 to illustrate the confidence limits for V_{50}, V_{05} and V_{95}. In this case the V_{05} is important as it predicts the velocity at which there is only a 5% chance of penetration. It can be seen that for all batches, cracked or A1 the V_{05} is above the upper limit of the proof velocity. It must be emphasized that the V_{05} and V_{95} are extrapolations from the collected test data which was close to the V_{50}. Consequently the confidence limits on the V_{05} are relatively large. The 95% confidence limits (i.e. the range within which we are 95% certain the true value lies) are tabulated for V_{05}, V_{50} and V_{95}. It can be seen that not only do the V_{05} values all lie above the proof test velocity but that in only one case does the 95% confidence limit of the V_{05} drop marginally lower than the proof test velocity. In practice it is unlikely that performance of the panel will drop below the proof test velocity. However, the model predicts that statistically we cannot be (95%) sure that there would only be a small (5%) chance that penetration would occur.

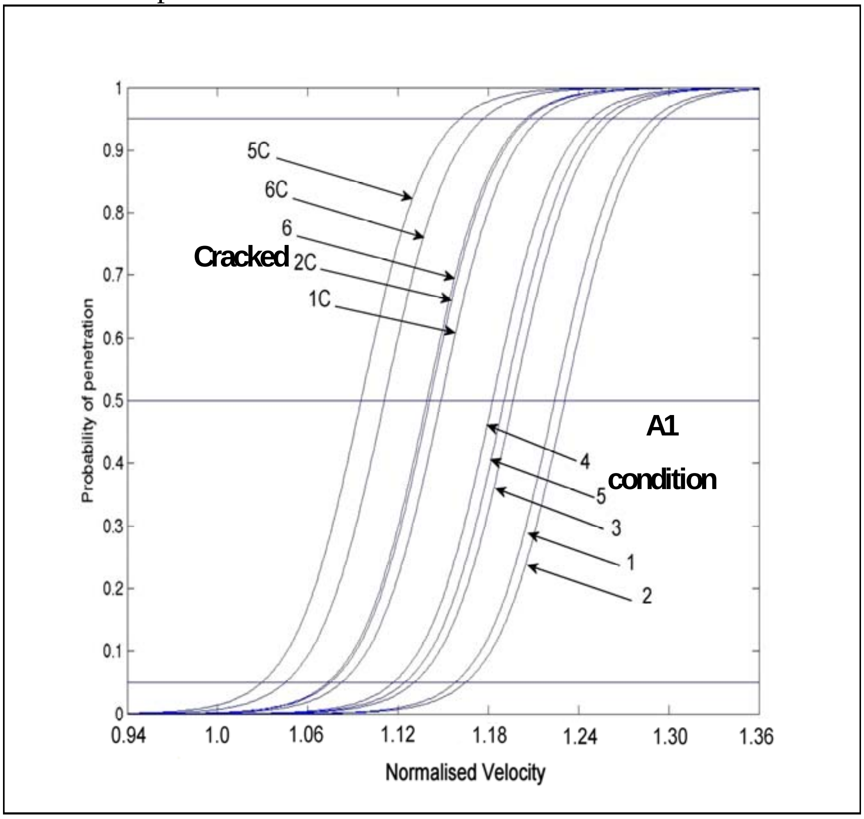

Figure 5. Fitted models of probability of penetration vs velocity normalised with the specified velocity limit equal to 1

Table 2. Confidence limits for the values of calculated V_{05}, V_{50} and V_{95} ms^{-1}

Batch No C = cracked		V_{05} and 95% Confidence limits			V_{50} and 95% Confidence limits			V_{95} and 95% Confidence limits		
	n	Lower limit	V_{05}	Upper Limit	Lower limit	V_{50}	Upper Limit	Lower limit	V_{95}	Upper Limit
6C	6	0.98	1.05	1.09	1.07	1.12	1.16	1.14	1.18	1.25
6	18	1.01.	1.08	1.11	1.11	1.15	1.17	1.19	1.21	1.26
5C	7	0.96	1.03	1.07	1.06	1.10	1.14	1.13	1.17	1.23
5	15	1.07	1.13	1.16	1.17	1.20	1.23	1.24	1.27	1.33
4	8	1.05	1.10	1.16	1.15	1.19	1.23	1.22	1.26	1.32
3	23	1.08	1.14	1.16	1.18	1.21	1.23	1.25	1.27	1.33
1C	21	1.03	1.09	1.12	1.13	1.16	1.18	1.19	1.22	1.28
1	21	1.11	1.17	1.19	1.21	1.23*	1.26	1.28	1.30	1.35
2C	21	1.02	1.08	1.11	1.10	1.15	1.17	1.19	1.22	1.27
2	24	1.12	1.17	1.20	1.22	1.24*	1.26	1.28	1.31	1.37

For example, the normalised V_{50} for cracked plates is 1.1 of the specified velocity range with 95% confidence that the true V_{50} lies between 1.06 and 1.14. The graphs of the fitted model in figure 4 show that older and cracked plates have lower estimated V_{50}'s than later batches, while the confidence intervals in table 3 show the degree of uncertainty attached these estimates. For example, in table 3 the un-cracked plates from batch 2* have a slightly higher estimated V_{50} than those from batch 1*, (*highlighted in table) but the overlap of their confidence limits shows that this apparent difference is probably due to chance. However, both have higher true V_{50}'s than plates from batch 6 cracked or un-cracked.

Confidence intervals are narrower for batch/crack combinations with larger data sets as its effect can be estimated more precisely. The confidence intervals for the V_{05} and V_{95} are wider than those for the V_{50}'s. The reason for this is that the data were collected according to the UK/SC/5449[3] method for estimating V_{50}'s, which mean that in order to establish a V_{50} the majority of the shots were at velocities close to the V_{50}. Because of the large data set at velocities close to the V_{50}, the estimates and confidence intervals for the V_{50}'s are accurate as these are based on interpolation. However, the low number of data collected for some of the tests on cracked plates, e.g. 6C which had only 6 data points grouped around the V_{50}, (highlighted in column n in table 2) meant that in these cases the V_{05} and V_{95} predictions were extrapolations beyond the range of velocities used in the trial.

CONCLUSIONS

It was shown that both the A1 condition and pre-cracked plates from all year batches would meet the current UK/SC/4898[1] specification.

The statistical analysis found that irrespective of plate condition (A1 or cracked) for most batches the (V_{05}) is above the specified velocity limit. For the pre-cracked batches 5 and 6, the 95% confidence limit for the predicted figure does fall below the limit but it is likely that the accuracy of this confidence interval is affected by the low number of shots fired.

Older batches of plates (3 to 6) had a slightly lower performance than more recent batches (1&2). However, it was also found that more than one type of ceramic had been used within these batches, therefore some variability between manufacturers and type of ceramic may account for the slight difference in performance.

A1 condition plates with slight cracks met the specification, but had a 4-10% reduction in V_{50} when compared to A1 condition plates without any imperfections. The reduction in mean V_{50} performance of cracked plates compared with A1 varied from 3.9% for the oldest (batch, No 6) to 7.7% for one of the most recent (batch No 2). However, irrespective of crack type, the ballistic performance of cracked plates remained at least 10% above the specification V_{50} velocity.

X-ray examination has shown that it will accurately detect the presence of cracks so therefore verify the true condition of the plates. However, boundary conditions need to be established for rejection, as plates with cracks were shown to meet the requirements of UK/SC/4898[1].

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