# EFFECTS OF BOUNDARY CONDITIONS ON V50 AND ZONE OF MIXED RESULTS OF FABRIC ARMOR TARGETS

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We assessed the effect of boundary conditions (BCs) on $V_{50}$ and zone of mixed results (ZMR) of square fabric targets against Remington 9mm 124 grain parabellum bullets. We examined two fabric constructions, two target sizes and four BCs (edge clamps with three levels of edge constraint, and on clay), in a designed experiment. The constructions were multiple plies of Kevlar KM2® fabric at ~5 kg/m$^2$, laid up similar to military vests. We analyzed target $V_{50}$ and ZMR, and bounded 90% confidence intervals of $V_{50}$ for each size and BC with probit analysis of the pooled shots (~80 per size/BC). We captured high-speed movies of selected shots, and examined bullets recovered from those shots.

Boundary conditions significantly influenced $V_{50}$ and ZMR. BCs that make fabric impact response more homogeneous through the test yield more consistent results. Clay backing and the strongest edge constraint gave the most consistent results. Decreasing edge constraint gave decreasingly consistent results, and increasing dependency on target size. Increasing target size gave lower $V_{50}$ and higher variability for all edge conditions except clay. Highest edge constraint gave highest $V_{50}$, agreeing with the literature. Clay backing gave the lowest $V_{50}$, agreeing with conventional wisdom.

## INTRODUCTION

Despite their rarity as a battlefield threat, civilian pistol bullets are frequent quality assurance projectiles for flak jackets [1, 2]. It is critical that the inherent variability of the testing itself introduce known and minimal variability, to allow the end user the highest confidence in discriminating articles consistent with an approved design from those inconsistent with an approved design. Three obvious, potential sources of testing variability arise from boundary conditions (BCs) [3,4], target size, and the target material.

## EXPERIMENTAL

To study these potential sources of variability and their potential interactions, we performed a designed experiment to assess $V_{50}$ with Remington 124 grain 9 mm full metal jacket bullets, using four boundary conditions that have been considered for flak jacket quality assurance testing, two target sizes (380 mm×380 mm and 457 mm×457 mm square targets), and two different target constructions.

We used a full factorial design with four replicates per BC, size and target construction, for 4×2×2×4 = 64 total targets. We used a range set up like that described in NIJ 0101.04, Figure 6, except for the target shape and boundary conditions. We shot all targets 10 times, in a consistent pattern (75 mm away from edges, 75 mm horizontally and 25 mm vertically from previous shots), starting at 480-490 m/s, and varying velocity up-and-down depending on arrest or perforation. $V_{50}$ was the average velocity of arrest/perforation pairs within 38 m/s (6-10 shots). BCs are shown in Figure 1; target constructions are given in Table 1. Clay was conditioned per NIJ 0101.04.

We analyzed the $V_{50}$s and zones of mixed results (ZMR) using a general linear model (GLM) for linear and quadratic effects of *BC*, *size* and *target construction*, and pooled results of all shots on each BC/size combination to estimate $V_{50}$ and confidence interval. For some combinations of conditions, we also filmed impacts with high-speed cameras and examined partially penetrating projectiles.

## RESULTS

The GLM fitted $V_{50}$ with adjusted $R^2$ values of 81%, suggesting BCs, target construction and target size and their interaction terms could account for most of the variability in $V_{50}$. BCs, target construction and target size, as well as the interaction term (BCs × construction), were significant ($P < 0.05$). Figure 2 plots significant effects for $V_{50}$ and ZMR, respectively. Changing BCs from clay to on-air shooting with the highest restraint against fabric pull out at the grips increased average $V_{50}$ by 36 m/s, or 8%. The other significant effects could change $V_{50}$ ~10 m/s, or ~2%. Increasing target size from 380 to 457 mm side length appeared to decrease $V_{50}$, both as a main effect and as an interaction term with construction. However, the interaction term (BC × size), which was nearly significant ($P=0.09$), showed minimal effect of size on $V_{50}$ when tested on clay, and increasing effect with decreasing edge restraint when tested on air. This is seen in Figure 4, in which $V_{50}$ and 90% confidence intervals were fitted from a logistic regression of each combination of BC and size (80 shots per population).

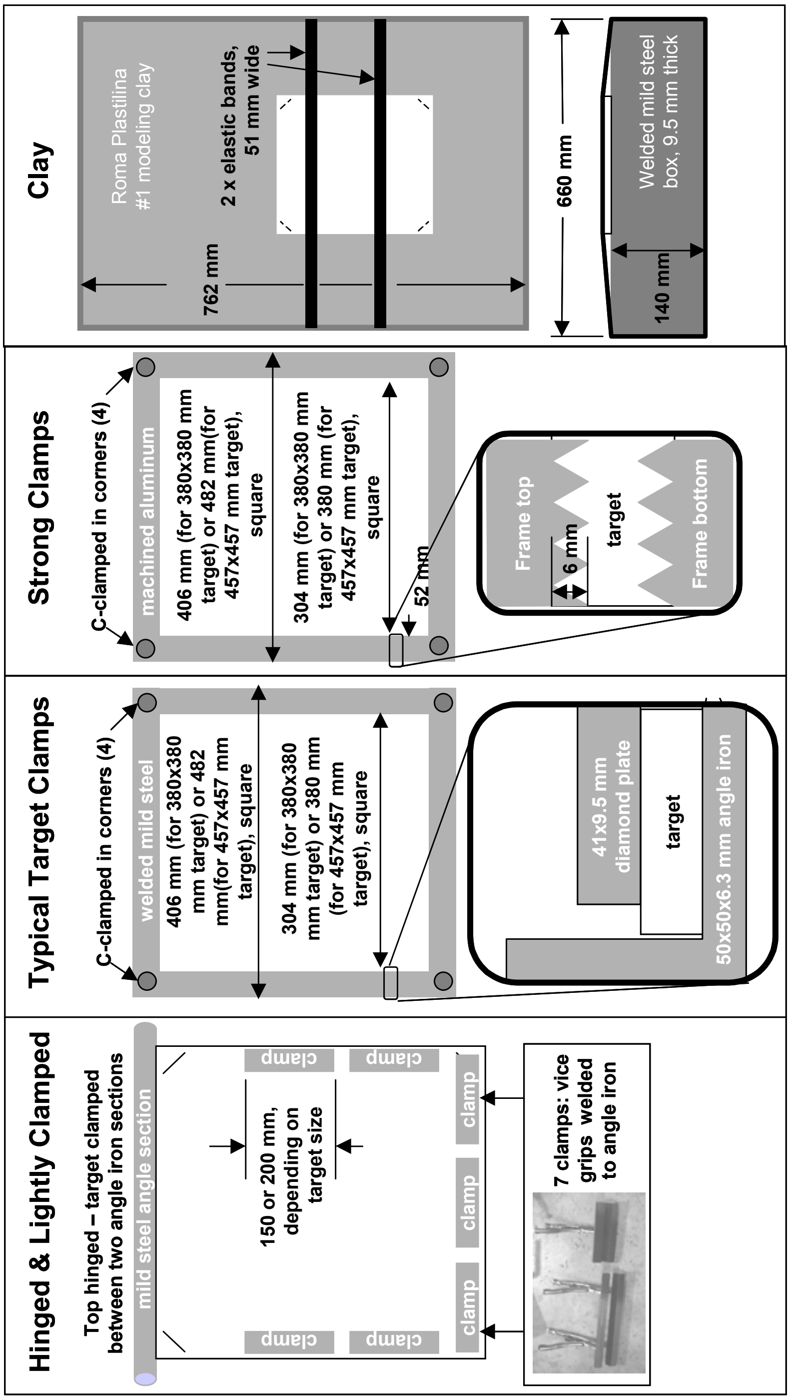



Figure 1: Boundary conditions (BCs).

**Table 1: Target constructions.**

| Construction | # plies | Yarn type | Yarn size (dTex) | Weave pattern | End Count (yarns/10 cm) | Conditioned Target Areal Density (kg/m$^2$) | Weaver | Finish |
|---|---|---|---|---|---|---|---|---|
| 1 | 28 | Kevlar KM2® | 660 | plain | 134 | 4.97 | Hexcel | CS-898 |
| 2 | 11 | Kevlar KM2® | 440 | plain | 114 | 4.64 | Hexcel | CS-898 |
| | 17 | Kevlar KM2® | 660 | plain | 110 | | Hexcel | CS-898 |
| | 11 | Kevlar KM2® | 440 | plain | 114 | | Hexcel | CS-898 |

ZMRs for similar tests had more variation than $V_{50}$. As a result, the GLM predicted only 39% of the RMS error, and BCs were the only significant term for ZMR. Figure 3 plots the average effect of BCs on ZMR. Clay gave the lowest ZMR (~2 m/s average). This may be explained in part by fewer tests per target used on clay (six / target, vs 10/target for targets shot on air). For edge restrained targets tested on air, ZMR increased with decreasing edge restraint, from an average of 12 m/s with a deeply toothed, strong clamp to 24 m/s with the hinged and lightly clamped support.

Figure 5 shows a series of images from high speed movies of a target back face from the shot location nearest the corner, in a non-perforating impact. The target was the hinged / lightly clamped BC, 457x457 mm, and construction 1. The classical, pyramid-shaped deformation (e.g., [5]) rapidly loses symmetry as fabric flows into the impact location from the two close edges. Figure 6 shows a similar series of images from a similar target, with the strong clamp BCs. The out-of-plane deformation retains two symmetry planes longer, corresponding to reduced fabric pull out at the clamped edge. The bullet impacting the hinged / lightly clamped target was not axially symmetric after impact, while the bullet impacting the strongly clamped target was essentially axially symmetric after impact.

## DISCUSSION AND CONCLUSIONS

Boundary conditions and target size impact both average perforation velocity and testing variability in 9mm FMJ tests on soft armor targets. Changing BCs or size moved average $V_{50}$ more than 10 m/s; changing BCs moved ZMR similarly. Flak jackets are usually selected to have the minimum safety margin necessary to ensure compliance with performance requirements, to minimize cost and weight. It is reasonable to speculate that flak jackets designed to pass frequent lot acceptance tests have a 3-5 standard deviation ($\sigma$) safety margin, and that $\sigma$~10-15 m/s. Effects examined could thus dramatically change lot acceptance test failure rates by increasing or decreasing safety margin several $\sigma$. Our data suggests a viscous material backing reduces test variability and sensitivity to target size, but at lowest average $V_{50}$.

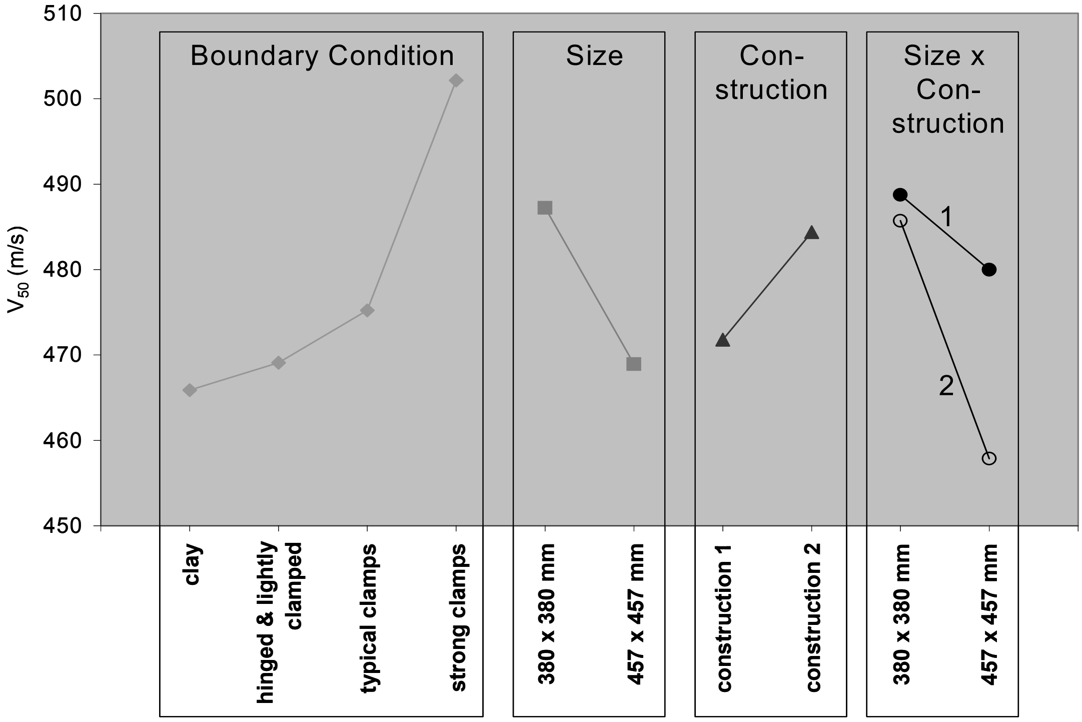



**Figure 2: Significant effects on target $V_{50}$, from general linear model.**

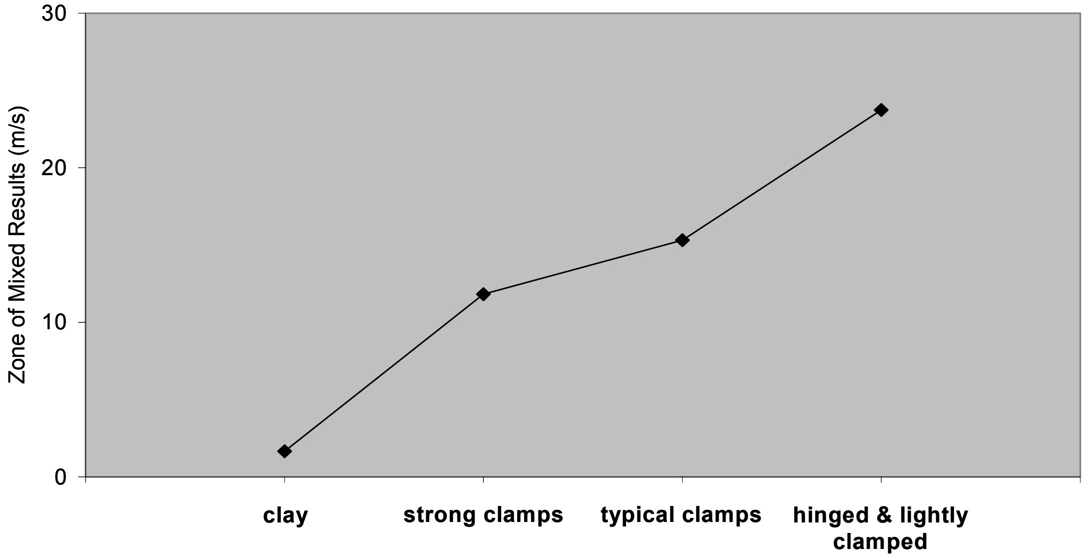



**Figure 3: Significant effects on target Zone of Mixed Results, from general linear model.**

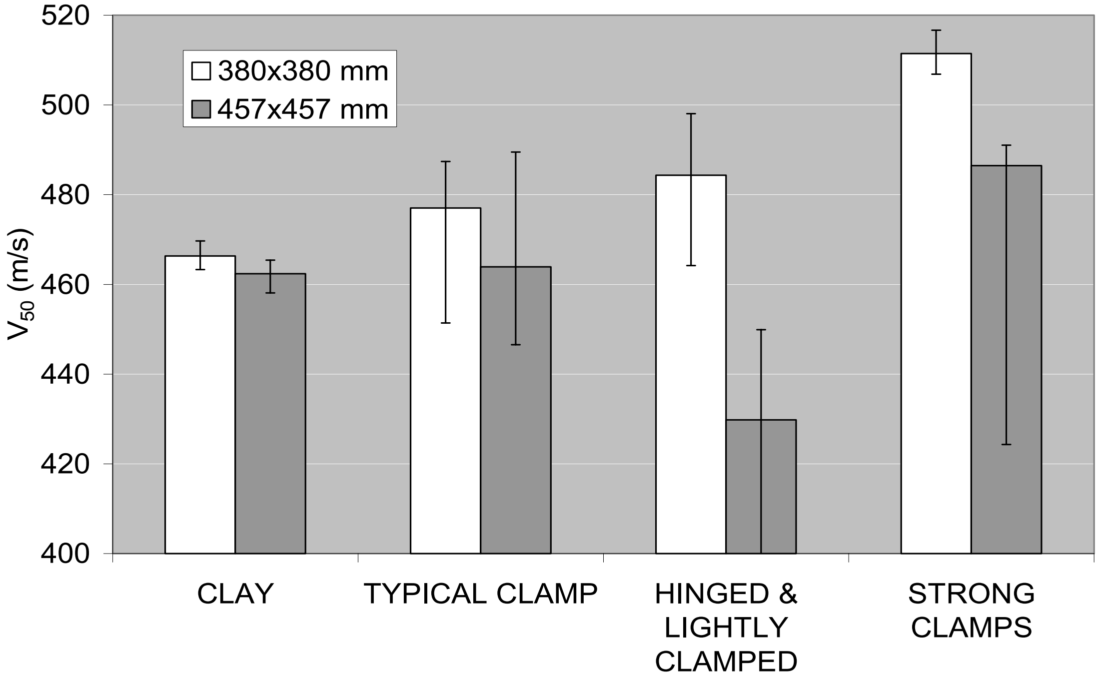



**Figure 4: $V_{50}$ and 90% confidence intervals from logistic regression of pooled shots for each boundary condition / size combination.**

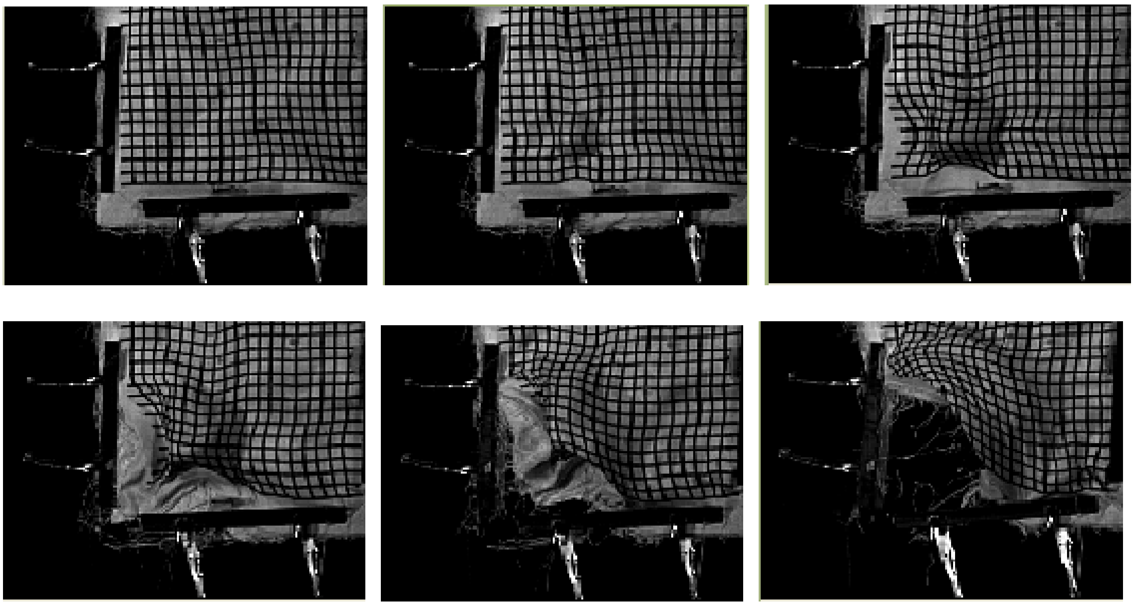
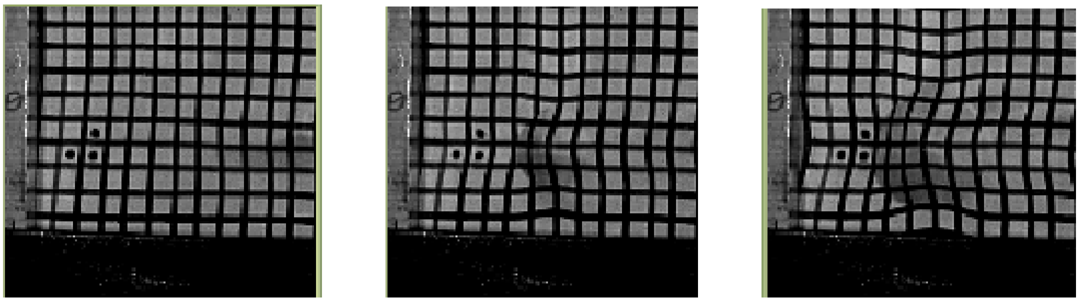


**Figure 5: Images from high-speed movies of impacts from the back of the target. Target is hinged along top (out of view), lightly clamped on the other three sides, from construction 1, 457×457 mm.**



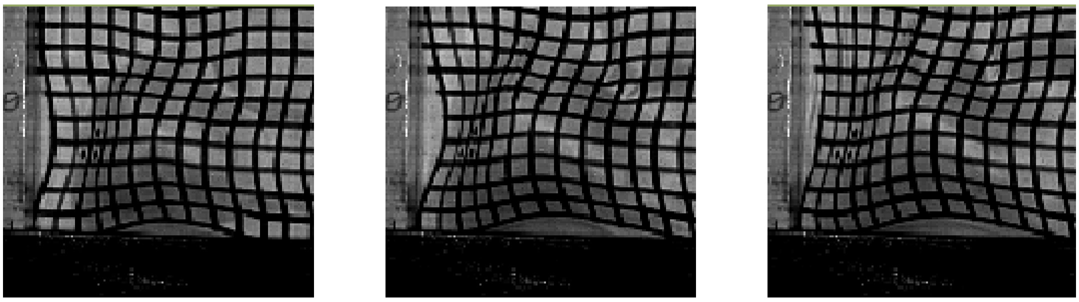


**Figure 6: Images from high-speed movies of impacts from the back of the target. Target is strongly clamped in deeply toothed clamp, from construction 1, 457×457 mm.**

We observed that the more the target is constrained to deform in a self-similar manner in each impact, the more consistent the test results will be, and the less sensitive they will be to target size. This is reasonable, given the critical role of out-of-plane deflection in soft armor projectile arrest (*e.g.*, [5]). In addition to decreasing variability, strongly impeding fabric pull out at the target edges appears to increase soft armor $V_{50}$, as was reported in [3,4].

## REFERENCES

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