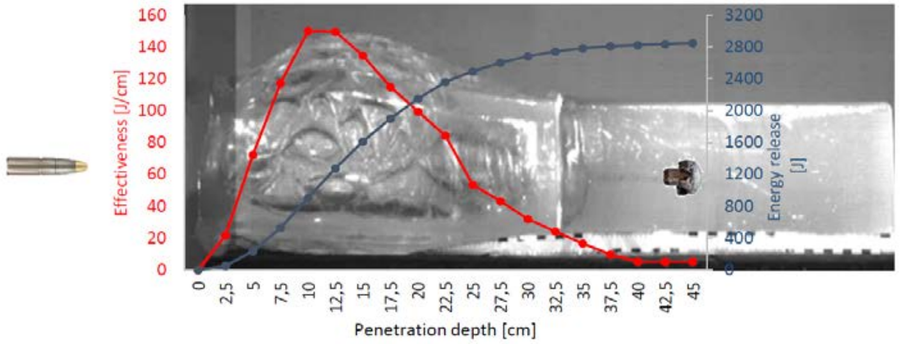
Suitability of two gelatin block sizes as ballistic simulant for hunting bullets tested with 2,900 J



15.03.2024, BfR

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Overview

1. Experimental setup for shooting
2. Preliminary work for the measurement of crack lengths
3. Results of crack length measurement
4. Considerations of the physical effectiveness [J/cm] of the bullet

Aims

- Testing the load capacity of the two gelatin block sizes.

⬇

Frequently used hunting bullet

⬇

Higher number of gelatin blocks

- Application of the modified method for crack length measurement based on photo should be further investigated and statistically validated by a larger sample size.
- Investigation of the influence of gelatin block size on the energy release profiles and their reproducibility.

Hypotheses

When testing two gelatin block sizes by firing a high-energy hunting bullet, it is expected that

a) the small block size will not withstand the high energy release of the bullet and that the block will rupture

b) the large block size will withstand the high energy release of the bullet.

Experimental setup for bombardments

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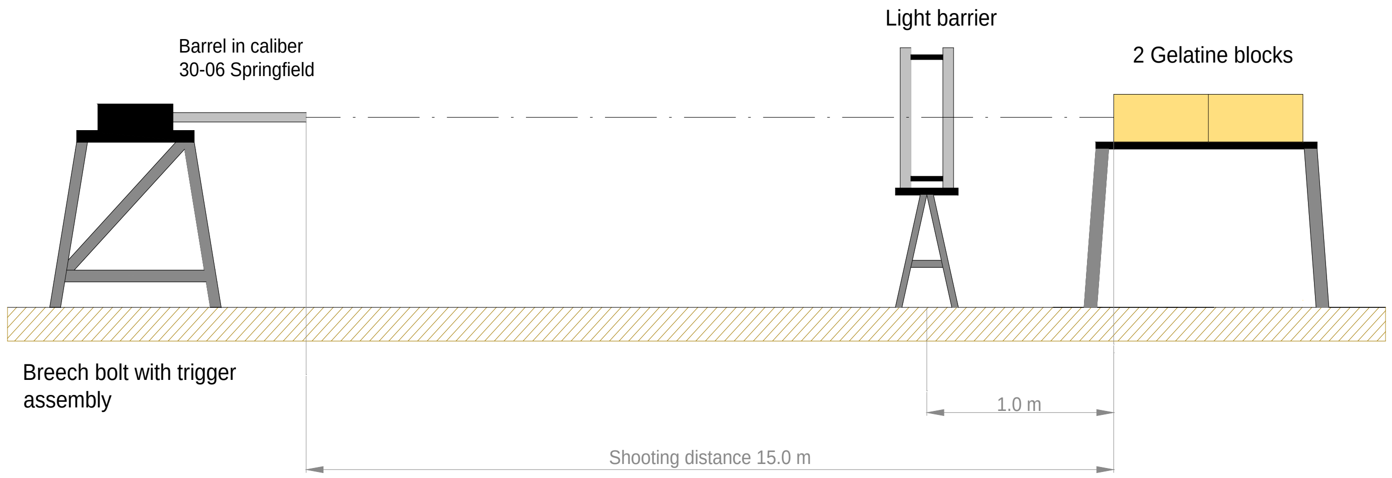
Experimental conditions

Part II

- RWS Evolution 11.9 g, Caliber 30-06 (leaded deformation bullet)
- Target (Bullet) Energy: 2,900 J
- Bullet target (impact) velocity: 700 m/s (± 10 m/s tolerance level)
- Shooting distance of 15 m (Simulated approx. 100 m)
- Infrared precision light barrier recorded the impact velocity of the bullet (1.0 m in front of the front of the block)
- Two blocks were always positioned one behind the other

Part I

- RWS 338 Lap. Mag. SPEED TIP PRO 16,2
- >5,000 J
- 800 m/s
- One gelatin block per shot



Test simulant

12 x 2* gelatin blocks (20 % gelatin) in the following dimensions:

- 6 small blocks*: 35 x 15 x 15 cm (length x height x width)
- 6 large blocks*: 40 x 25 x 25 cm (length x height x width)

*For each shot on 6 small blocks and 6 large blocks, two blocks were always positioned one behind the other.

Preliminary work for the measurement of crack lengths

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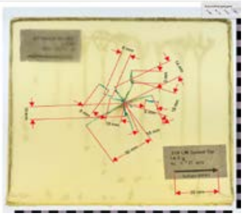
Crack lengths analyzer and crack length method used

* Source: TR Patrone 9 mm x 19, schadstoffreduziert (2009)
** Proposed by BfR
*** www.imagej.nih.gov/ij (Proposed by Nosler)

Circular template (Mitutoyo RA1.30 – 201388)

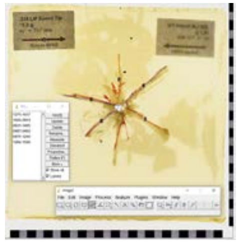
Direct measurement* → Beschussamt Ulm → Reference } Location-dependent (immediately after the shot)



Adobe Reader DC** → Germany 1, Germany 2, Germany 3, Germany 4

Photo printout → Germany 5

7 gelatin blocks



ImageJ*** → USA 1, USA 2, USA 3 (4 gelatin blocks); USA 4, USA 5, USA 6 (3 gelatin blocks)

Location-independent (photobased)

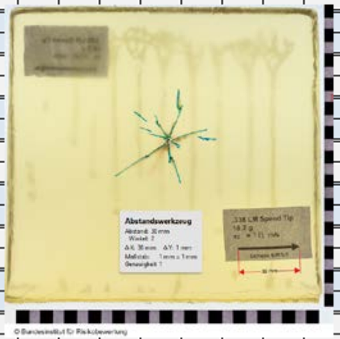
The crack lengths of 7 evaluable blocks were measured by 9 crack lengths analyzer.

Input template and calculation of the crack length (photo-based crack length measurement-large block size)

First gelatin block (40 cm ≙ 16 slices)

Second gelatin block

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
1	Block 12	Penetration			j: crack length number																									Si.front/	
2	Slice number i	depth	Site	Arrow	j=1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Si.back	LTotal.i
3	1	0,0 cm	VS		7,2																									7,2	62,2
4		2,5 cm	RS		21	6,2	6	5,9	7,1	13	5,9	6,3	8,3	9,1	11	17														117,1	
5	2	2,5 cm	VS		34	3,9	9,6	12	23	23	21	4,1	21	6,4	12	13														183,5	247,4
6		5,0 cm	RS		29	34	26	11	26	6	20	24	9,7	17	13	20	19	10	40	7,7										311,3	
7	3	5,0 cm	VS		30	24	24	22	14	21	15	20	29	24	12	20	2,4	15	48	17										336,5	426,5
8		7,5 cm	RS		47	35	22	24	58	10	26	22	28	6,2	30	36	22	13	38	43	37	19								516,5	
9	4	7,5 cm	VS		23	29	21	4,8	31	39	8,4	26	35	16	4,7	37	11	19	28	9,2	1,5	59	51	46						498,5	476,5
10		10,0 cm	RS		59	40	63	9,5	9,8	36	12	20	38	16	14	7,2	7,2	17	37	34	28	8,9								454,5	
11	5	10,0 cm	VS		32	32	26	2,8	23	9,7	22	20	46	48	21	43	12	2,8	47	63										447,8	463,2
12		12,5 cm	RS		30	5,6	34	17	68	43	26	51	23	19	34	24	37	29	25	12										478,5	
13	6	12,5 cm	VS		40	8,1	12	4,5	13	11	15	48	36	13	17	44	22	40	29	5,4	67	32	9,5	27						494,5	501,1
14		15,0 cm	RS		40	12	51	26	36	8,4	9,6	60	25	25	17	11	14	6,4	27	33	5	48	19	3,6	30					507,7	
15	7	15,0 cm	VS		17	2,2	32	54	33	3,2	23	28	9,1	30	8,2	8,4	39	27	7,3	25	14	25	22	26	34	35				501,2	460,5
16		17,5 cm	RS		55	28	21	9,1	45	42	51	31	47	23	13	3,4	13	14	23											419,7	
17	8	17,5 cm	VS		21	16	7,5	11	49	37	18	30	42	43	15	30	4,1	20	23	24	55									443,8	396,5
18		20,0 cm	RS		14	14	25	10	25	27	18	20	2,1	65	23	16	23	9,7	22	16	18									349,1	
19	9	20,0 cm	VS		7,2	17	11	4,9	9,4	22	31	7,6	58	11	13	21	20	2	23	16	19	30	6,4							330,1	331,4
20		22,5 cm	RS		20	24	25	12	10	49	60	25	36	18	39	15														332,6	
21	10	22,5 cm	VS		20	17	2,3	27	15	34	32	17	32	25	7,4	16	11	12	11	2,8	16	17								312,9	240,9
22		25,0 cm	RS		19	2	11	8,7	2,8	11	6,3	11	11	27	14	22	20	4,4												168,9	
23	11	25,0 cm	VS		20	11	23	7,6	17	15	20	11	20																	144,2	149,6
24		27,5 cm	RS		19	6,5	6,8	8,4	25	20	9,4	13	4,8	19	13	12														155	
25	12	27,5 cm	VS		25	31	16	18	27	14	15																			146	113,3
26		30,0 cm	RS		24	9,9	30	17																						80,5	
27	13	30,0 cm	VS		17	32	8,8	19																						77,2	77,2
28		32,5 cm	RS		25	15	23	15																						77,1	
29	14	32,5 cm	VS		16	22	9,1	7,3	17																					70,2	55,8
30		35,0 cm	RS		18	13	10																							41,3	
31	15	35,0 cm	VS		14	7,8	9,6	5,5																						36,7	38,1
32		37,5 cm	RS		12	9,7	9,6	8,4																						39,5	
33	16	37,5 cm	VS		7,2	7,8	7,3	7,9																						30,2	23,0
34		40,0 cm	RS		3,2	4,8	7,8																							15,8	
35	17	40,0 cm	VS		8,7	1																								9,7	9,6
36		42,5 cm	RS		5,3	3	1,2																							9,5	
37	18	42,5 cm	VS		6,4																									6,4	6,6
38		45,0 cm	RS		5,6	1,2																								6,8	
39	19	45,0 cm	VS		2,2	2,5																								4,7	7,65
40		47,5 cm	RS		4,3	6,3																								10,6	
41	20	47,5 cm	VS																											0	0
42		50,0 cm	RS																											0	
43	21	50,0 cm	VS																											0	0
44		52,5 cm	RS																											0	
45	BfR																													LTotal	4087
46		Bundesinstitut für Risikobewertung										Beschussamt Ulm																			



$$L_{Total.i} = \frac{1}{2} * (S_{i.front} + S_{i.back})$$

$$L_{Total} = \sum_i L_{Total.i}$$

Abbreviations

L Crack length [mm]

S Slice

i Slice number

j single crack number

$S_{i.front}$ Crack length sum (slice i front)

$S_{i.back}$ Crack length sum (slice i back)

Statistical analyses

Generalized additive models (GAMs)

1. Association between the used crack length measurement tool and crack lengths (for six shots)

$$L_{Total.i} = \beta_0 + s(penetration\ depth, bs = \text{"cr",k=5}\ ) + s(analyzer, bs = \text{re}) + measurementTool + \ \varepsilon$$

Gaussian family

2. Association between the crack length analyzer and the number of cracks (for six shots)

$$Number\ of\ cracks = \beta_0 + s(penetration\ depth, bs = \text{cr}) + crack\ length\ analyzer + \varepsilon$$

Negative binomial family

- $L_{Total.i}$ is crack length of slice i as response variable
- β_0 is the intercept term, it denotes the overall mean of the response
- s(penetration depth) is a smoother that accounts for the path of the bullet through the block
- k denotes the degree of smoothing
- s(analyzer) is a random effect smoother for the nine crack length analyzers
- "Measurement tool" is a categorical term with reference category "Beschussamt Ulm" (Measurement directly after shooting) and two measurement tools (AdobeReader DC, ImageJ, Photo printout) at a later time and location-independent
- Crack alalyzer is a categorial term with the reference category "Beschussamt Ulm"
- ε is a Gaussian error term (the unexplained variation)

Results of crack length measurement

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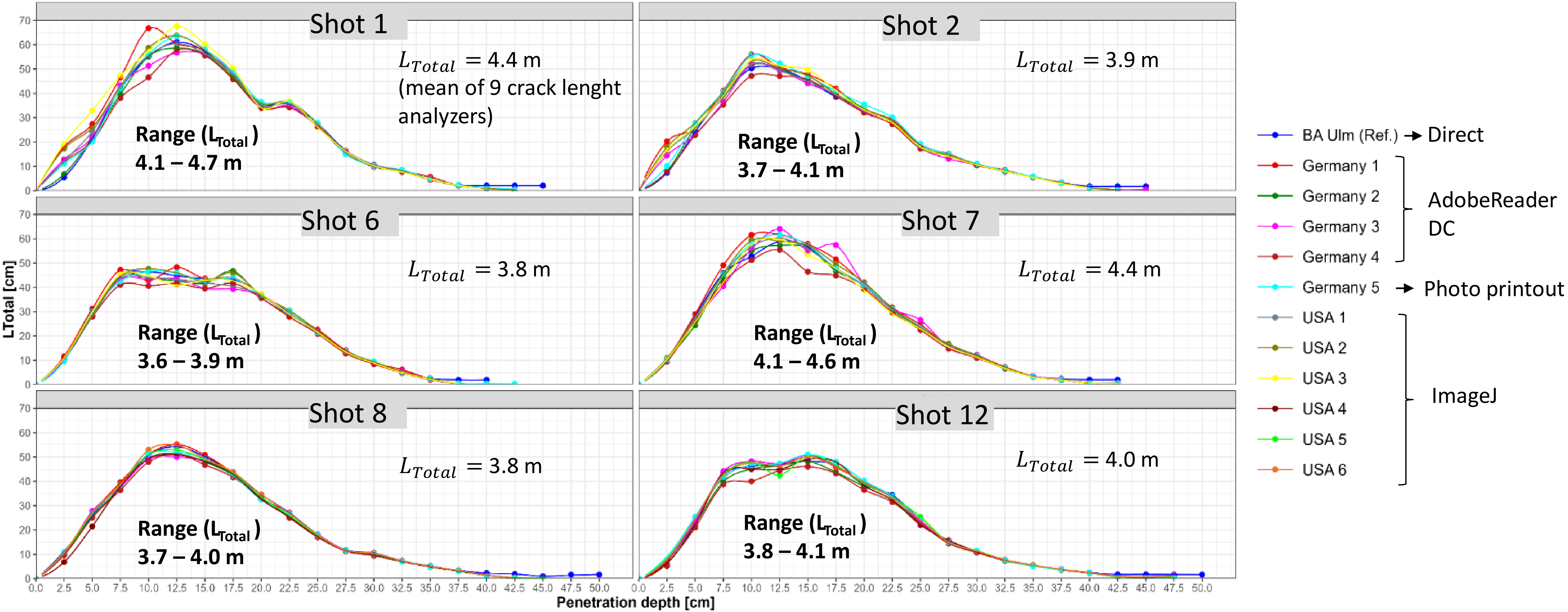
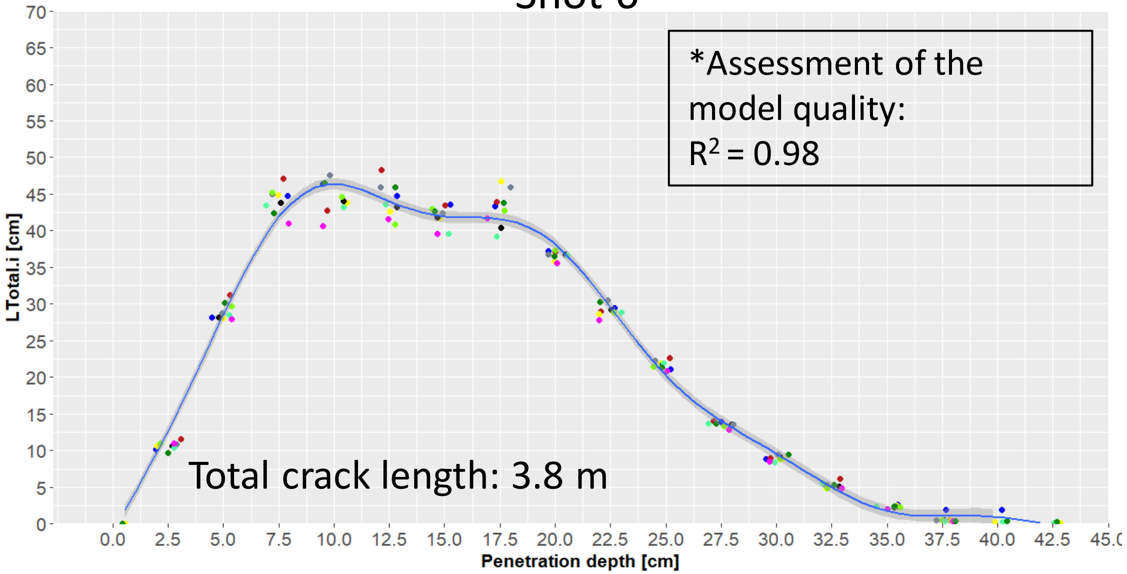
Course of the crack lengths measured with different methods



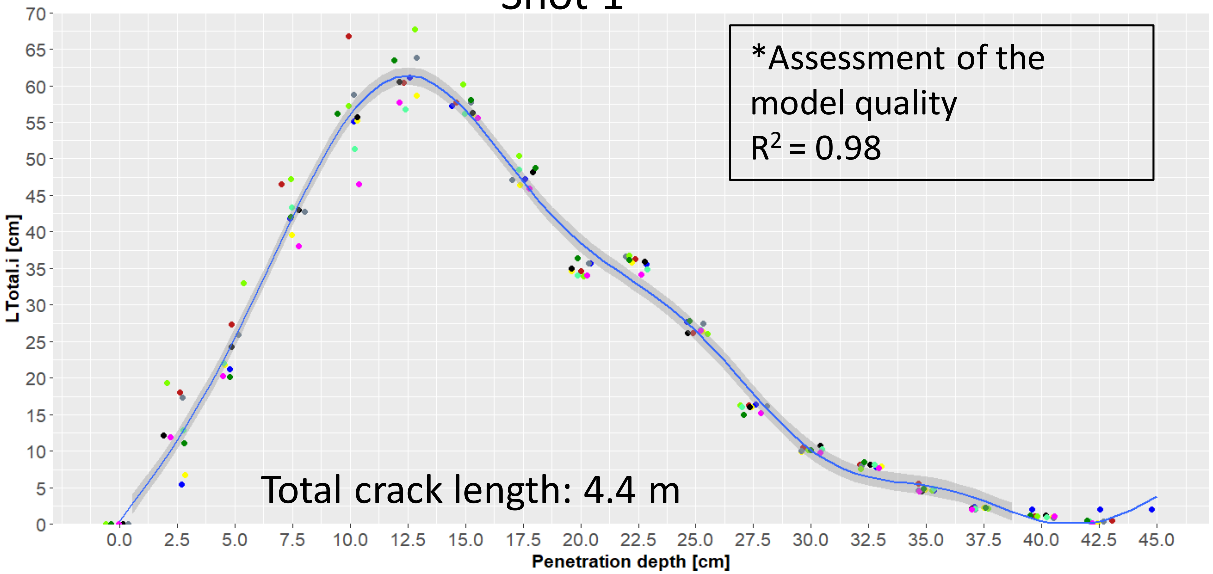
No significant differences between the reference method (blue line) and the three crack lengths methods on photo basis ($p>0.05$).

Course of crack lengths of shot 6 compared to shot 1
Prediction model

Shot 6



Shot 1



- BA Ulm (Ref.)
- Germany 1
- Germany 2
- Germany 3
- Germany 4
- Germany 5
- USA 1
- USA 2
- USA 3

Generalized additive model (GAM)

$$L_{Total\_i} = \beta_{0+} s(penetration\ depth, bs = \mathrm{cr}) + s(crack_{analyzer}, bs = \mathrm{re}) + \varepsilon$$

$$\varepsilon \sim N(0, \sigma^2)$$

*Assessment of the model quality:
R^2: quadratic correlation between the observed and predicted result values.

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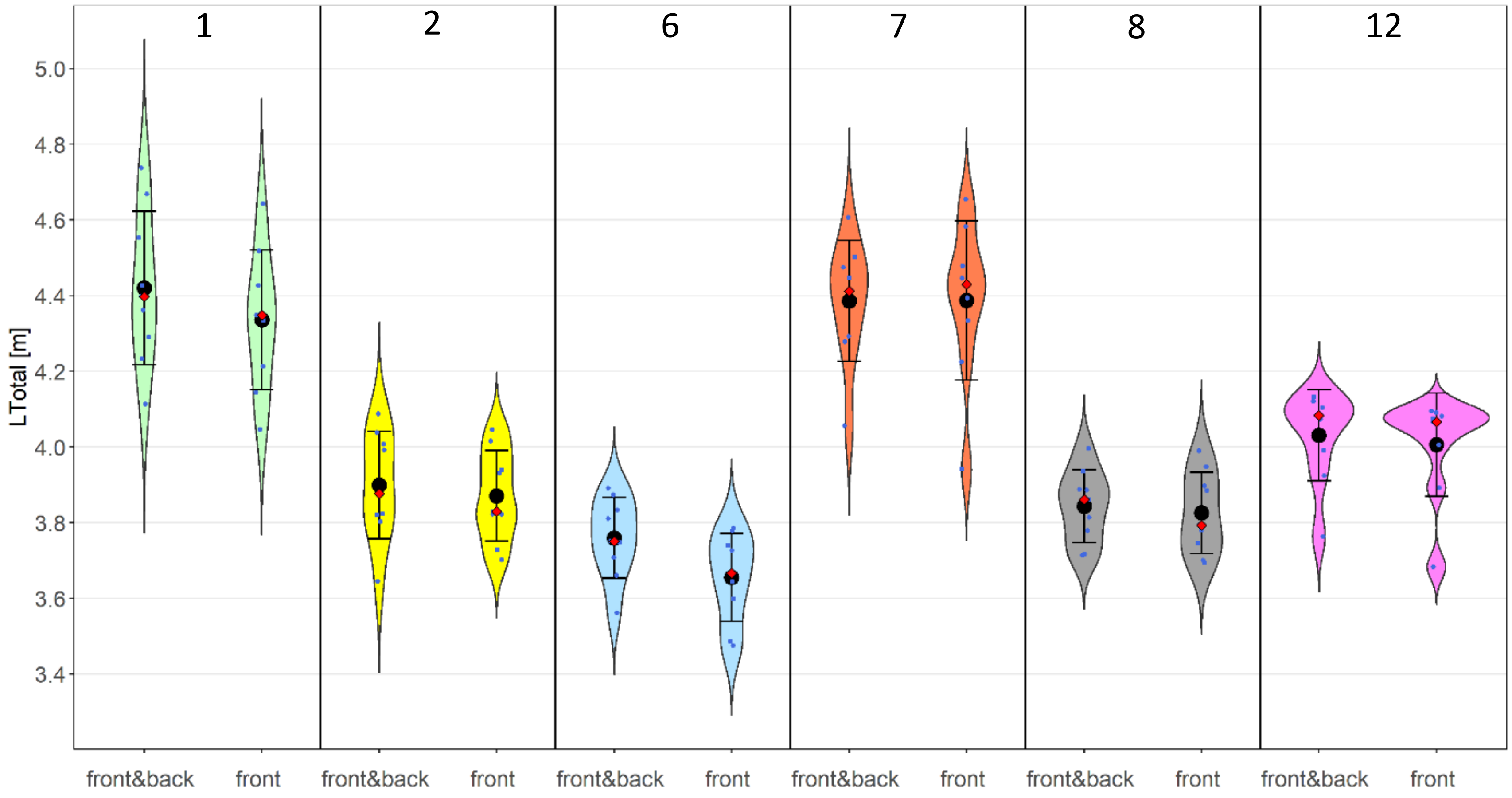
Effects of the omission of crack lengths on the back ($S_{i.back}$) of each slice on the total crack length (L_{Total})

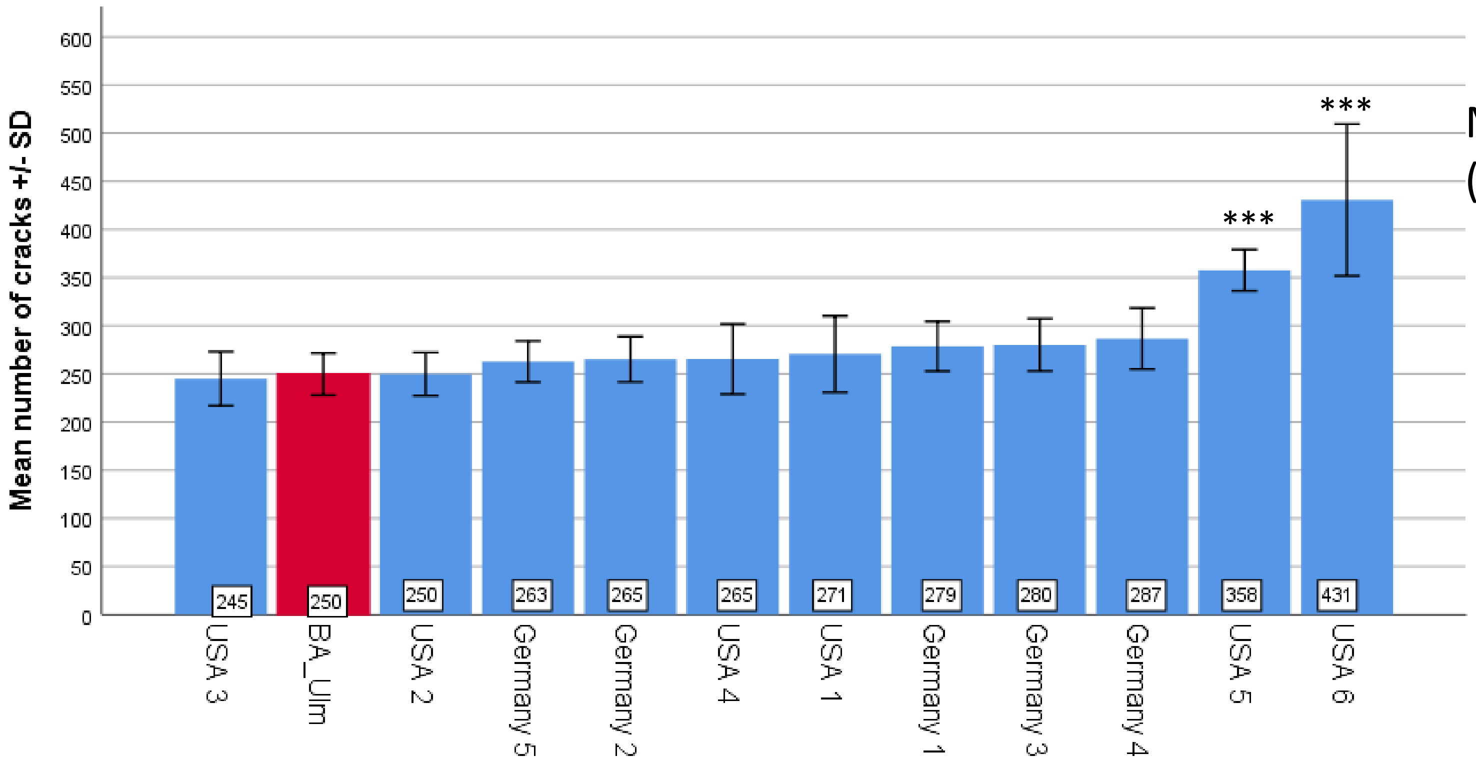


Black error bars representing the standard deviations of the means (black dot), red dots represent the median, blue dots (jittered) represent raw data of individual crack length analyzers, shape of violin plots represent the density distribution.

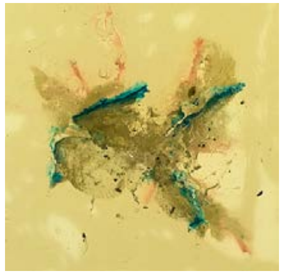
*Paired Wilcoxon exact-rank test from R package "exactRankTests"

Omitting the crack lengths on the back side of each slice had no significant* effect on the total crack length (for all 6 shots on large gelatin blocks).

Evaluation of the mean number of cracks depending on crack length analyzer



Mean number of cracks measured (average of 6 large and 1 small block)



***p<0.001 (gam. family: Negativ Binomial, Reference Ulm)

$$Number\ of\ cracks = \beta_0 + s(penetration\ depth, bs = \mathrm{cr}) + crack\ length\ analyzer + \varepsilon$$

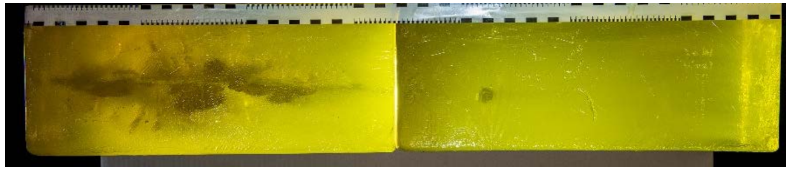
Considerations of the physical effectiveness [J/cm] of the bullet

Calculation of the total energy release ($E_{rel.Total}$) of the bullet in the gelatin block (20 %) – TR Patrone 9 mm x 19

1. $$W_i = \frac{E_{kinTarget}}{s * L_{Total}} \cdot L_{Total.i}$$

The effectiveness W_i is defined as energy release $E_{rel.i}$ over a certain distance (for slice i with thickness s=2.5 cm).

$$E_{kinTarget} = \frac{m}{2} V_{Target}^2$$ ⇨



⇨ $$E_{kinRest} = \frac{m_{Rest}}{2} V_{Rest}^2 = 0$$ ⇨ V_{Rest}= 0 when bullet got stuck

---

2. $$E_{rel.Total} = \sum E_{rel.i}$$ ⇨ $$E_{rel.i} = \frac{E_{kinTarget}}{L_{Total}} \cdot L_{Total.i}$$

$$E_{rel.Total} = E_{kinTarget} - (E_{kinRest}) = \sum E_{rel.i}$$

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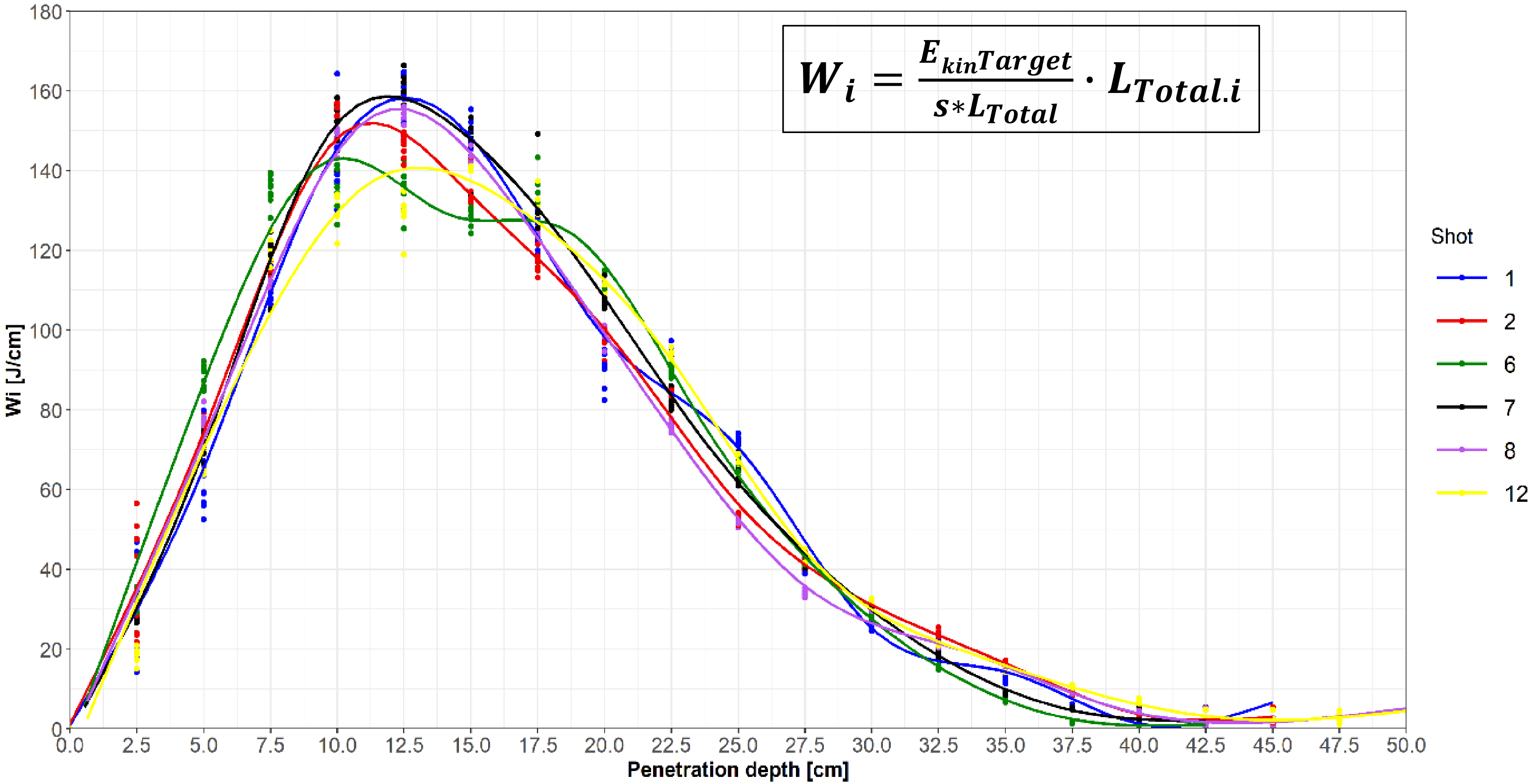
Effectiveness [J/cm] of the bullet from six shots on large gelatin blocks



$$W_i = \frac{E_{kinTarget}}{s * L_{Total}} \cdot L_{Total.i}$$

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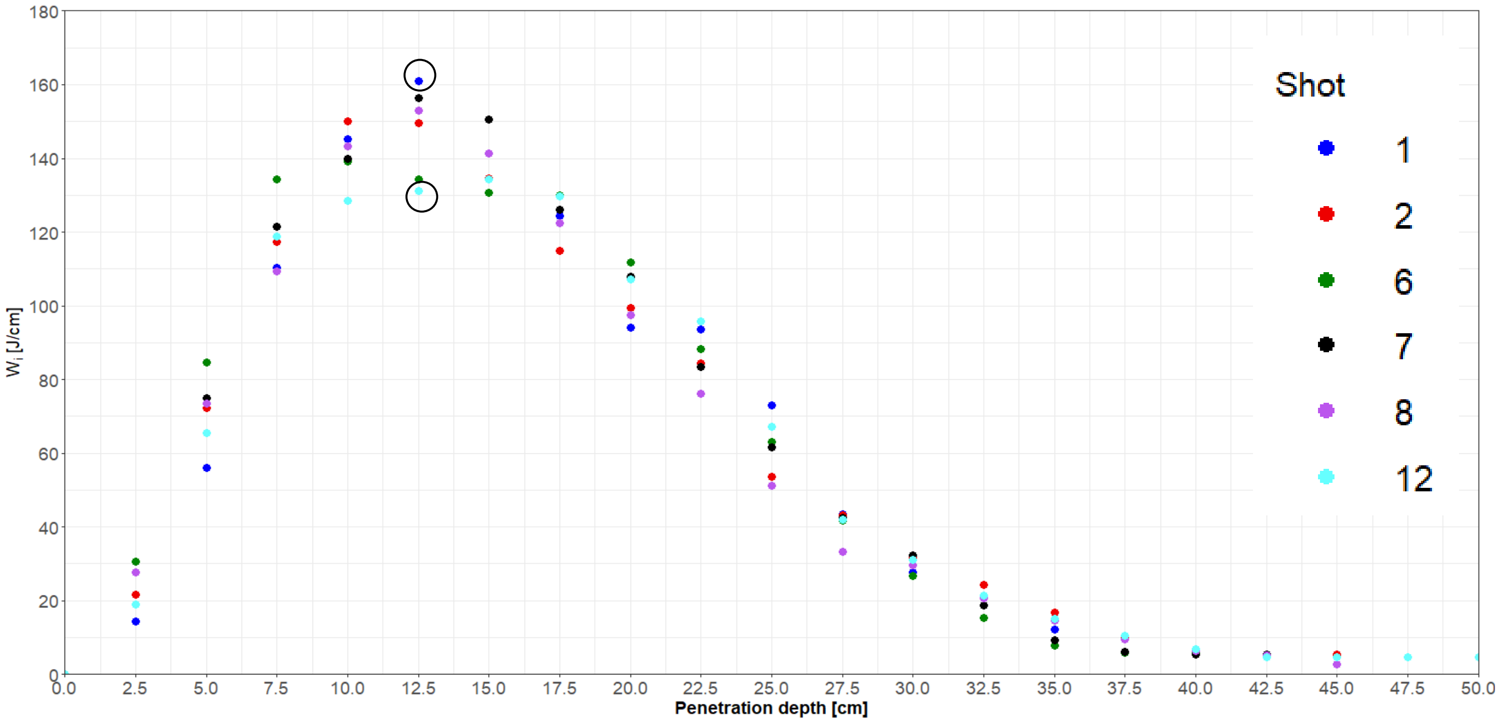
Maximum Effectiveness [J/cm] of the bullet from six shots on large gelatin blocks

Shot	1	2	6	7	8	12
V_{Target} [m/s]	695	692	695	701	688	693
W_{max} [J/cm] - Reference	161	150	139	156	153	134

Max effectiveness $W_{i.max}$ (J/cm):
From 134 (shot12) to 161 (shot1)

Difference: 27 J/cm
(at same target speed)



Summary

Small block size 35 x 15 x 15 cm (length x height x width)

- Five out of six small blocks cracks emerged on the outer sides of the blocks ➡ could not withstand the energy of the bullets.
- Result of the small block is a single event (one of six) – random result.
- Smaller block size might not suitable for bullet testing.

⬇

In order to obtain reproducible results, a large number of small gelatin blocks would have to be shot.

⬇

Associated with high effort and cost.

Summary

Large block size: 40 x 25 x 25 cm (length x height x width)

- Cracks do not go to the outside of the blocks at an energy of approx. 2,900 J.
- Photos of slices with the cracks were well suited for measuring cracks.

→ excellent photos by Sara Graetz

→ by marking the front and back sides with different colors

- An immediate evaluation does not yield significantly different results than the later evaluations on the computer.
- Crack lengths provide almost identical results with different measurement tools.
- Measurement of the crack lengths on the backs of the slices can be omitted (No general statement - depends on velocity and bullet).
- It is not necessary to measure very small cracks (<4 mm). These cracks do not affect the total crack length of the blocks.
- By placing two gelatin blocks next to each other, the energy release curve ("effectiveness") could be calculated along the penetration depth.

Conclusion

- The results from the first part of the study could be confirmed on the basis of a larger number of bombardments.
- Physical effectiveness of a bullet could be simulated in the gelatin test medium.

Acknowledgement

Ulm
Beschussamt Ulm

DEVA
Deutsche Versuchs- und Prüf-Anstalt
für Jagd- und Sportwaffen e.V.

DJV
Deutscher Jagdverband

OMI -Mellrichstadt

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Results of shots on gelatin blocks (Beschussamt Ulm-Reference)

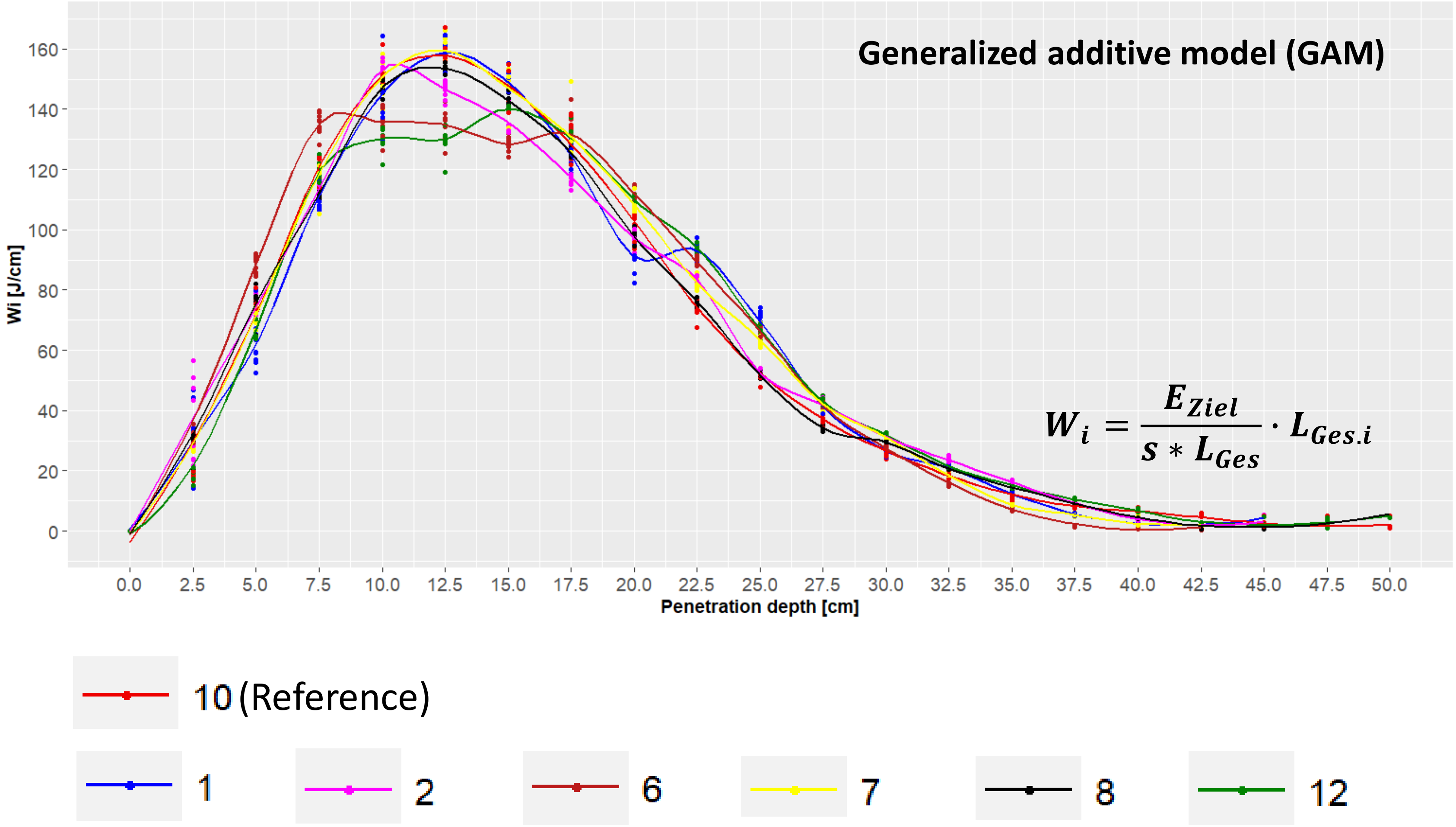
RWS Evolution 11.9 g, Caliber .30-06

Shot	*V_{Target} [m/s]	End position of the remaining bullet [cm]	Number of cracks	Total crack length L_{Total} [m]	Kinetic energy E_{Target} [J]	Energy release $E_{rel.Total}$ [J]	Max effectiveness $W_{i.max}$ (J/cm)	Rest diameter d_{Rest} [mm]	Rest bullet mass m_{rest} [g] (Loss of mass %)
1 (25x25x40 cm)	694.8	45	265	4.4	2872.3	2872.2	161	20.7	11.48 (3.5)
2 (25x25x40 cm)	692.1	45	234	3.8	2850.1	2849.7	150	17.9	11.18 (6.0)
3 (15x15x35 cm)	694.5	45	-	-	2869.9	-	-	17.9	10.72 (9.9)
4 (15x15x35 cm)	698.1	46.5	-	-	2899.7	-	-	18.5	10.70 (10.1)
5 (15x15x35 cm)	695.9	45	-	-	2881.4	-	-	16.8	9.93 (16.5)
6 (25x25x40 cm)	695.2	41	212	3.8	2875.7	2875.4	139	19.5	11.05 (7.1)
7 (25x25x40 cm)	**701**	44	280	4.4	**2923.8**	2923.5	156	20.0	10.89 (8.5)
8 (25x25x40 cm)	**688**	44.5	249	4.0	**2816.4**	2816.5	153	18.7	11.18 (6.0)
9 (15x15x35 cm)	706	50	-	-	2965.7	-	-	16.1	10.31 (13.4)
10 (15x15x35 cm)	695	51	254	3.7	2874.0	2873.8	158	16.4	10.12 (15.0)
11 (15x15x35 cm)	693	47.5	-	-	2857.5	-	-	17.5	9.9 (16.8)
12 (25x25x40 cm)	693	45	255	4.1	2857.5	2857.6	134	17.2	10.92 (8.2)

10 Small block (the only evaluable block out of a total of 6 blocks)

*The velocity level of the load with this bullet was 700 m/s (+/- 10 m/s tolerance level).

Comparison of the effectiveness of shot 10 (small block) with the effectiveness of the large blocks [J/cm]– Prediction model



Result: No significant differences between W_i of shot10 (Reference) and W_i of shots on large blocks.
The penetration depth has a significant influence on the effectiveness of the bullet ($p<0.01$).

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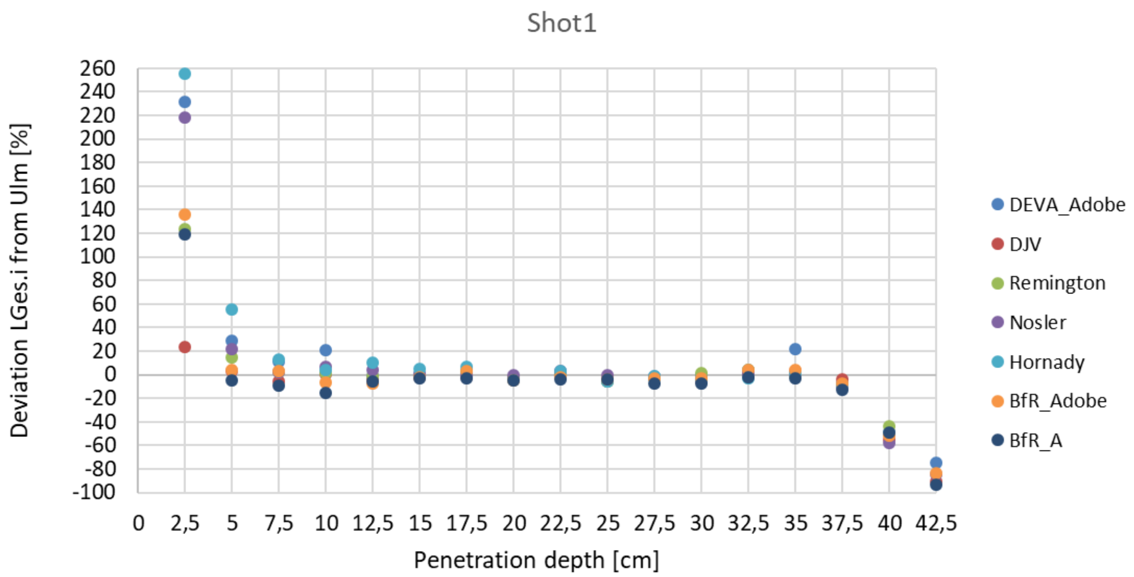
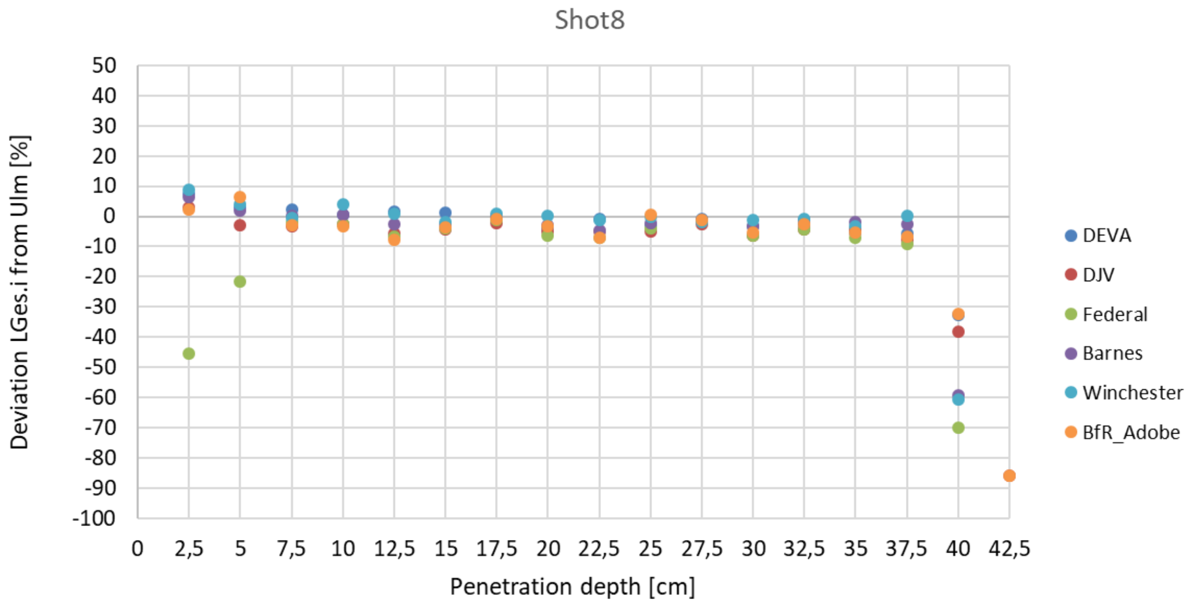
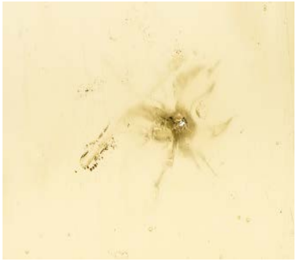
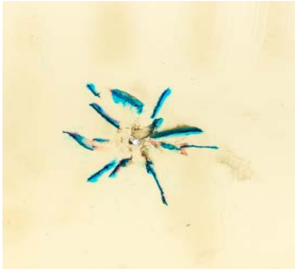
Percentage deviation of $L_{Ges.i}$ from reference values (Beschussamt Ulm)



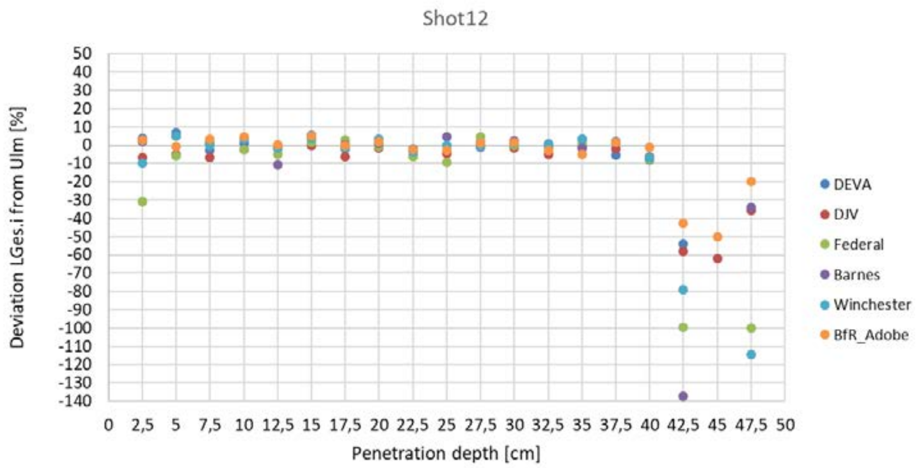




Shot1: Front Slice1 (Ulm: 7.7 mm)

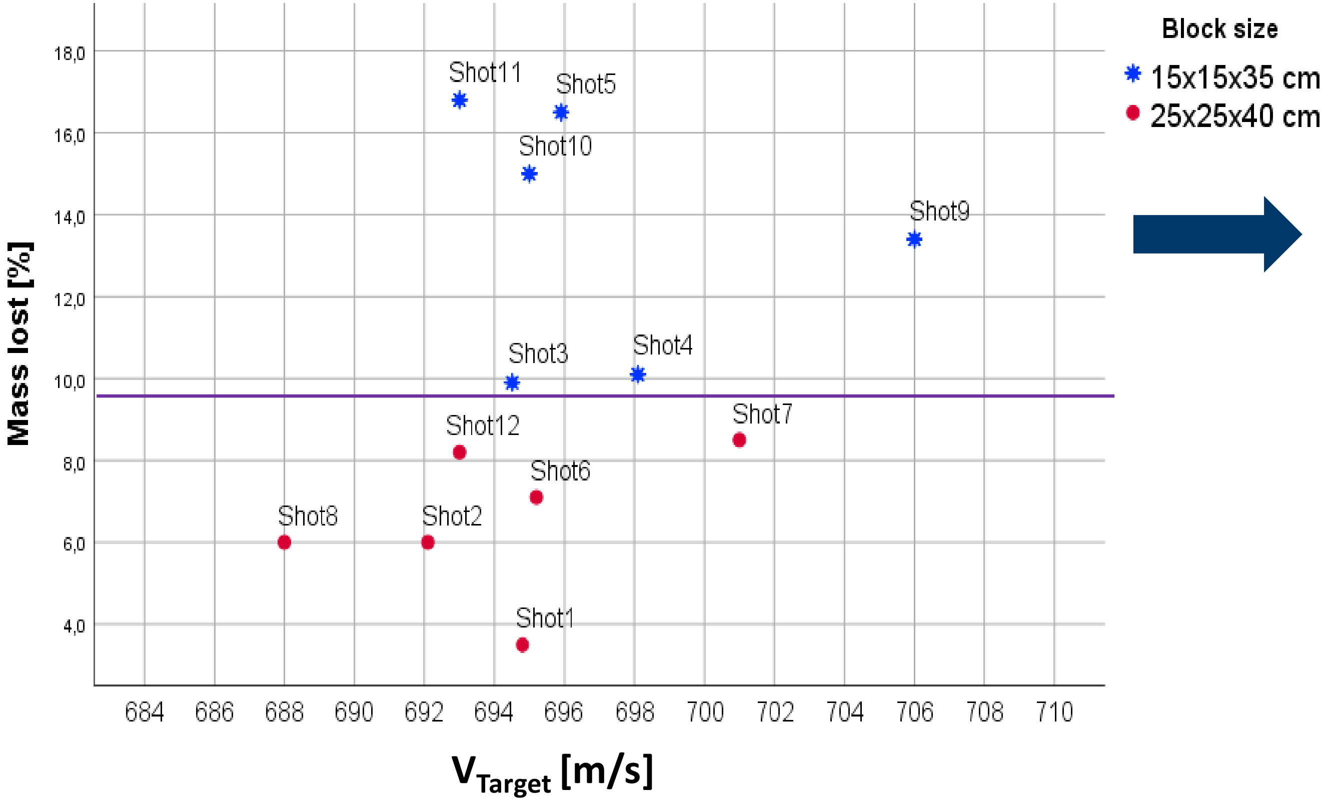


Shot1: Back Slice1



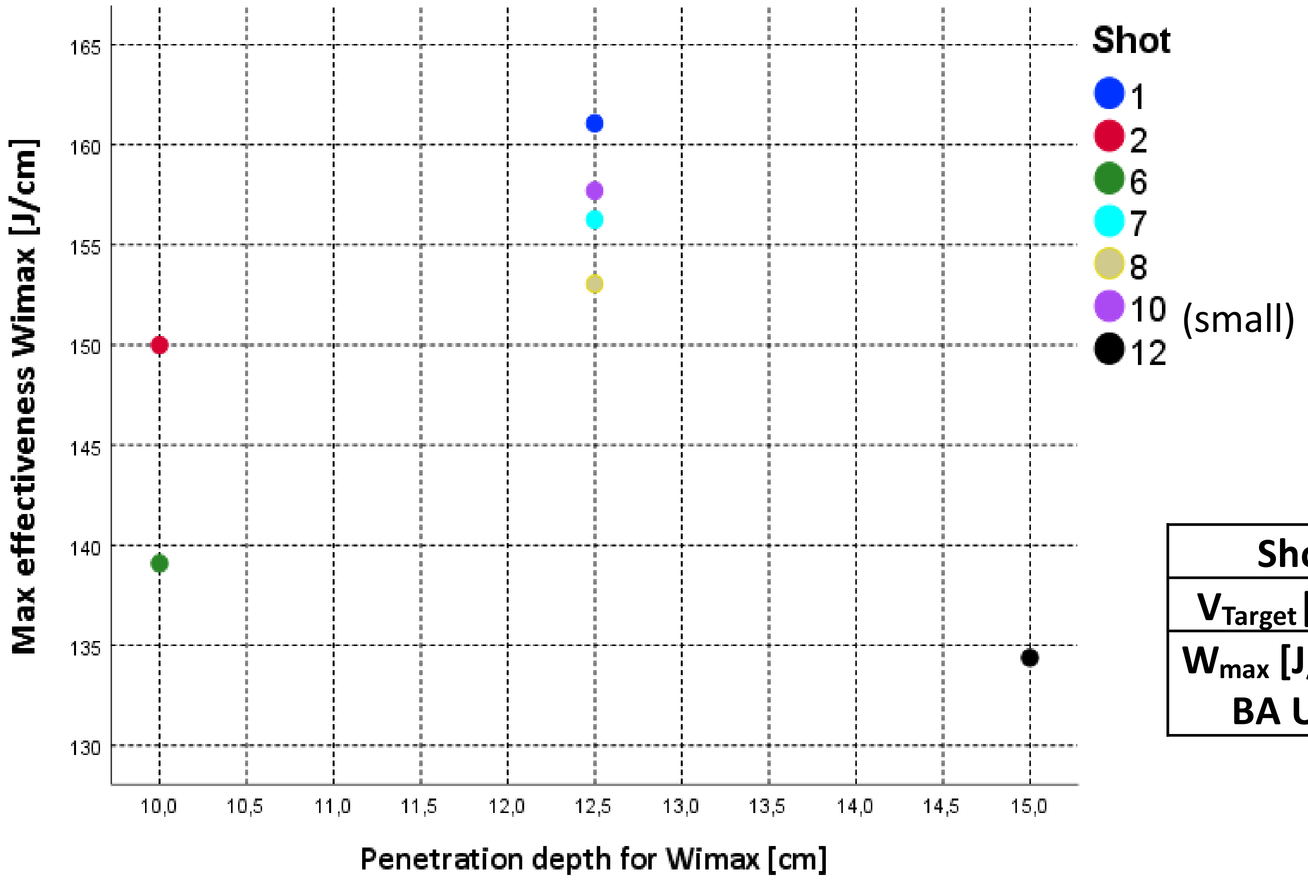
Mass lost of the bullet [%] depending on target velocity V_{Target} [m/s]

Bullet mass: 11.9 g



The mass loss of the bullets is higher when shooting at the small blocks at approximately the same target velocity.

Effectiveness maximum [J/cm] depending on the penetration depth for W_{imax}

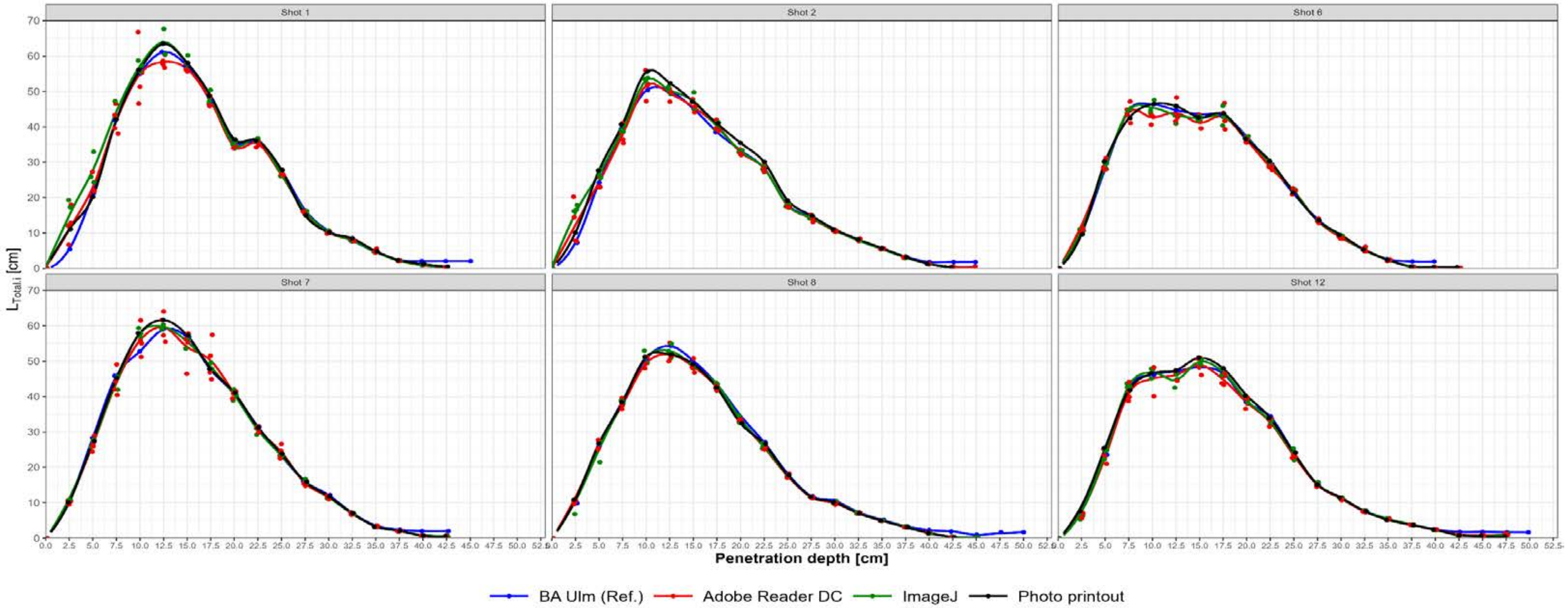


The largest variations between shots on six large gelatin blocks occur in the area of maximum effectiveness, i.e. after 10 to 15 cm penetration depth of the bullet.

Shot	1	2	6	7	8	12
V_{Target} [m/s]	695	692	695	701	688	693
W_{max} [J/cm] - BA Ulm	161	150	139	156	153	134

BfR

Comparison of photo-based crack length measurement tools (modified method) with direct measurement (Reference – BA Ulm)



$$L_{Total.i} = \beta_0 + s(penetration\ depth, bs = \text{"cr",k=5}) + s(analyzer, bs = \text{re}) + measurementTool + \varepsilon$$

No significant differences between the reference method (blue line) and the three crack lengths methods on photo basis (p>0.05).
gam. family: Gaussian

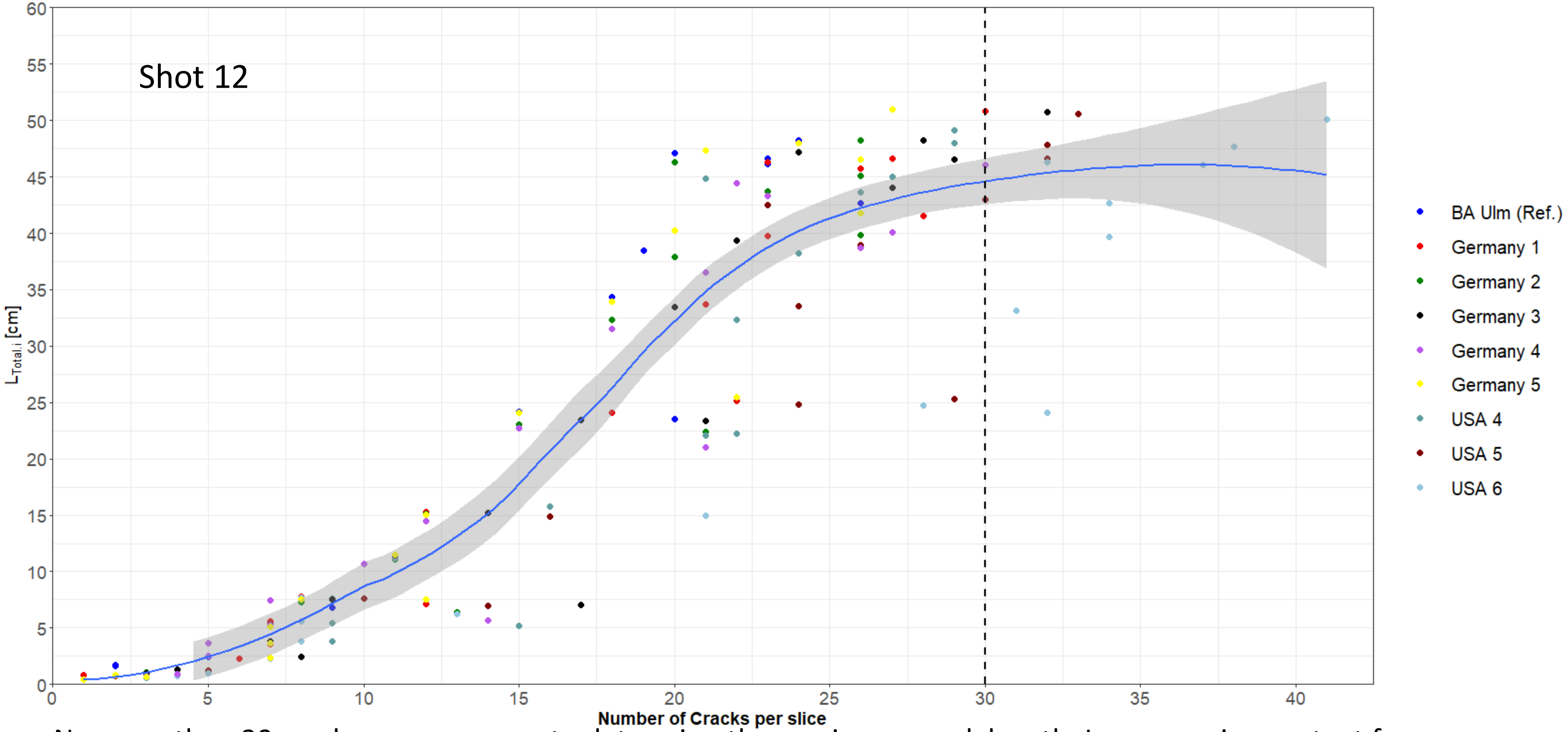
BfR

Summary

Uncertainties

- Elastic behaviour of the gelatin blocks avoids the formation of measurable cracks
- Due to the extreme inherent movements, especially with the small blocks part of the kinetic energy of the bullet is converted into other forms of energy

Relationship between crack length ($L_{Total.i}$) and number of cracks per slice



No more than 30 cracks are necessary to determine the maximum crack length. $L_{Total.i}$ remain constant from approx. 30 cracks.