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IMPACT EXPERIMENTS ON SCALED REINFORCED CONCRETE PLATES

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ABSTRACT

To investigate the influence of scaled plate parameters on the experimental data, impact experiments within a test series of 15 reinforced concrete (RC) plates were carried out at the drop tower facility of the Otto-Mohr-Laboratory of the Technische Universität Dresden, using the accelerated mode. Therefore, three different scales were used to reduce respectively enlarge the internal parameter of the RC specimen as well as the external parameter of the impactor equally. Five different impact velocity levels with three specimen each were realized. Finally, the local damage caused by spalling and scabbing as well as the global behaviour of the tested specimens were evaluated.

INTRODUCTION

Knowledge of the structural safety of the confinements of nuclear power plants against a possible aircraft impact is essential to ensure the safety of the plants. However, this is a very wide-ranging and complex issue. On the one hand, it is necessary to describe the load function and, on the other hand, the behaviour of the reinforced concrete (RC) members itself. The impact resistance of RC plates is influenced by numerous parameters such as used material, reinforcement content and the geometric properties e. g. thickness as well as the geometry and velocity of the used impactor. For experimental investigations, usually scaled tests are carried out instead of cost and time-consuming real size experiments. However, the fundamental question is to which degree these scaled experiments can be transferred to real scale.
This question has been addressed by various research teams in the past. Representative for all, Weber [8], Sugano et al. [7] and Horschel [6] as well as the research at Technische Universität Dresden by Just et al. [2], Hering et al. [3], [4] and Bracklow et al. [1] can be mentioned. While Weber [8] dealt with the issues of similarity physics across disciplines, the core topic of impact was taken up much more by Sugano et al. [7]. The focus of the Sugano group was more on the scalability of an engine and scaled representation around impact experiments. The behaviour of an impact loaded scaled target structure is discussed in the work of Horschel [6].

Partly based on this research, impact experiments with RC plates subjected to hard impact loads were carried out at the Institute of Concrete Structures at Technische Universität Dresden. For this purpose, a drop tower facility described in Just et al. [2] and Hering et al. [4] was designed, built, operated and used for experiments. In Just et al. [2], the scalability of the RC samples was examined theoretically and by a small number of own experiments. These were described in detail in Hering et al. [3], [4]. However, it turned out that the configuration of the used free-fall drop tower mode is only partially suitable for experiments to be scaled. This is due to the low variability of the impact velocity and the free-fall weight, which could only be increased in large steps (75 kg).

For this reason, the subject of the scalability of RC plates under hard impact loading was taken up again in Bracklow et al. [1]. For these experiments, the accelerated configuration of the drop tower facility was used. This allowed the impact velocities to be selected in a wider range. Furthermore, the impactor masses could be precisely scaled. A comprehensive summary of experiments can be found in Bracklow et al. [1]. The present publication focuses on 15 RC plates, which were tested specifically from the point of view of scalability.

EXPERIMENTAL SETUP

Used testing facility

The experiments were conducted in the drop tower facility at the Otto-Mohr-Laboratory of the Technische Universität Dresden. A detailed description of the facility is given in Just et al. [2]. For the experiments presented in this paper, the accelerated configuration was used. With this variant, an impactor with an outer diameter of 100 mm and a maximum mass of 100 kg can be accelerated with up to 16 bar boost pressure. The compressed air can be stored in two vessels with a net volume of 500 litres each. This allows an impactor to be accelerated up to 160 m/s.

Experimental programme and materials

The test programme was conceived in such a way that three different scales of RC plates could be tested with five test specimens per plate size. This results in 15 individual tests. Three plates (one of each scale) should be tested with the same impact velocity, which was controlled by regulating the loading pressure. In total five different velocity levels were realised.

Table 1: Similarity law for impact tests, according to Sugano et al. [7].

Parameter	Dimension	reference model	scaled model	Quantities
Length	L	d	$\varphi \cdot d$	L_1, L_2, = edge length of the plate $L_{1,s}$, $L_{2,s}$ = support length of the plate (span) H = thickness of the plate d_{rc} = reinforcement diameter d_{imp} = diameter of the impactor s_{rc} = reinforcement spacing L_{imp} = length of the impactor w_1 = displacement
Mass	M	m	$\varphi^3 \cdot m$	$m_{plate,1}$ = mass of the plate before experiment $m_{plate,2}$ = mass of the plate after experiment m_{sc} = scabbing mass m_{sp} = spalling mass m_{imp} = mass of the impactor
Time	T	t	$\varphi \cdot t$	time of the experiment
Velocity	LT^{-1}	v	v	v_{imp} = impactor velocity
Force	MLT^{-2}	f	$\varphi^2 \cdot f$	ΣLC = sum of measured reaction force

The scaling of the specimens was carried out according to the method summarised in Sugano et al. [7]. In reference to this, a factor φ was used for scaling. The mathematical correlations are summarised in Table 1. Based on this, the dimensions summarised in Table 2 resulted for the impactor based on factors φ = 1.00, 1.25 and 1.50. The different impactors are shown in the left picture in Figure 1.

Table 2: parameters of the used impactors.

φ [-]	d_{imp} [mm]	L_{imp} [mm]	m_{imp} [kg]	Shape of the impactor
1.00	66.7	200	5.44	
1.25	83.3	250	10.62	flat
1.50	100.0	300	18.40	

For all test specimens, a concrete C35/45 with a maximum grain size of 8 mm was used. The reinforcement consisted of conventional steel B500B. Diameters and spacings are given in Table 1. The reinforcement was placed crosswise in each plate as bending tensile reinforcement. The test specimens were produced in one charge, which ensures direct comparability, at least with regard to the concrete characteristics.

Test setup

In the accelerated configuration of the Dresden drop tower facility, a non-negligible challenge arose at the beginning. The impactors can only be accelerated in a defined way if they completely fill the acceleration tube (diameter = 100 mm). If this is not the case, the compressed air flows around the impactor and no real acceleration takes place.

Consequently, the impactors for the scaling factors φ = 1.00 and 1.25 had diameters that were clearly too small. Replacing the acceleration tube was not possible because of the enormous effort required. Therefore, a sabot for the impactors was made of XPS foam and applied, see in Figure 1 on the right.

Figure 1. Scaled impactors (left) and impactor with sabot during a preliminary test (right), photos: F. Bracklow

Measurement concept

Figure 2 shows on the left the measuring plan of the 4-point supported plates. During the experiments, on the one hand, the support reactions due to the impact event were measured by the load cells LC1 to LC4. The load cells used were designed and manufactured specifically for the drop tower facility. The measuring range is limited to 10 MN each. Further details on the load cells used can be found in Just et al. [2].

Secondly, the plate deformation was recorded in relative position to the centre of the plate (w_1) via a laser Doppler vibrometer (LDV). This method provides a contact-free measurement of the deformation and allows the measuring system to be placed at a safe distance from the striking point of the impactor.

On the right side of Figure 2 one can see the experimental setup in real conditions. This figure shows a plate (φ = 1.25) after the impact test. The four-point support of the plate onto the load cells is clearly visible. Furthermore, it can be seen that the plate is fixed to the load cells by means of threaded rods that lifting off is prevented. This fastening was done with a well-defined force of 25kN per load cell.

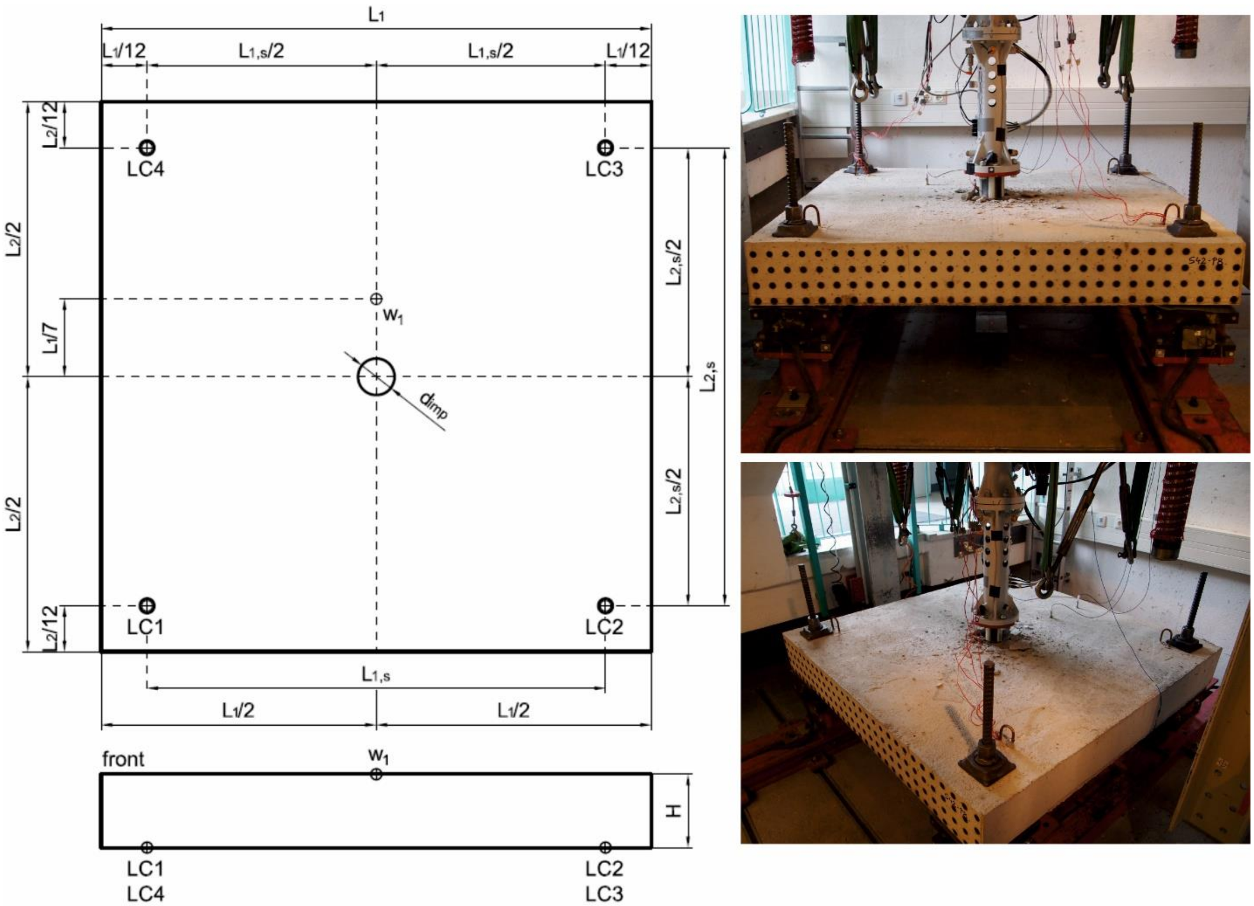

Figure 2. Parametric specimen dimensions and measuring plan (left) and view of the experimental setup (right), drawing: M. Hering; photos: F. Bracklow

EXPERIMENTAL RESULTS

The dimensions of the investigated RC plates are summarised in Table 3. Furthermore, the reinforcement parameters d_{rc} and s_{rc} resulting from the scaling were also compiled in this table. The velocity of the impactor v_{imp} and the plate mass before ($m_{plate,1}$) and after the experiment ($m_{plate,2}$) were added too in Table 3.

The mass of the plates after the experiments were derived according to equation (1). However, it was not easy to clearly classify the respective masses as spalling and scabbing. It was decided to classify all erupted material found on the top of the plate after the impact as spalling material (m_{sp}); all concrete pieces lying under the plate was therefore classified as scabbing material (m_{sc}). These values are also summarized in Table 3.

$$m_{\mathrm{plate},2} = m_{\mathrm{plate},1} - (m_{\mathrm{sc}} + m_{\mathrm{sp}}) \tag{1}$$

Table 3: Main experimental parameters and results.

Label	Label according to Bracklow et al. [1]	φ [-]	Dimensions and parameters [mm]		v_{imp} [m/s]	$m_{plate,1}$ [kg]	$m_{plate,2}$ [kg]	m_{sc} [kg]	m_{sp} [kg]
1.00 - 1	PL236		$L_1 = L_2 =$	1200	40.08	540.90	540.10	0.80	0.00
1.00 - 2	PL238		$L_{1,s} = L_{2,s} =$	500	48.28	543.30	543.22	0.00	0.08
1.00 - 3	PL235	1.00	$H =$	160	56.63	535.30	529.62	5.60	0.08
1.00 - 4	PL237		$d_{rc} =$	8	62.40	537.88	532.20	5.34	0.34
1.00 - 5	PL234		$s_{rc} =$	80	73.79	540.20	534.38	5.46	0.36
1.25 - 1	PL243		$L_1 = L_2 =$	1500	41.99	1063.40	1063.38	0.00	0.02
1.25 - 2	PL239		$L_{1,s} = L_{2,s} =$	625	48.97	1027.90	1020.48	7.30	0.12
1.25 - 3	PL241	1.25	$H =$	200	57.23	1033.20	1032.08	0.10	1.02
1.25 - 4	PL242		$d_{rc} =$	10	61.19	1035.50	1020.92	14.32	0.26
1.25 - 5	PL240		$s_{rc} =$	100	69.34	1038.40	1023.26	14.58	0.56
1.50 - 1	PL248		$L_1 = L_2 =$	1800	40.43	1785.80	1785.78	0.02	0.00
1.50 - 2	PL245		$L_{1,s} = L_{2,s} =$	750	47.15	1782.40	1779.96	1.80	0.64
1.50 - 3	PL246	1.50	$H =$	240	56.30	1785.50	1765.66	19.04	0.80
1.50 - 4	PL244		$d_{rc} =$	12	61.79	1776.60	1747.98	26.96	1.66
1.50 - 5	PL247		$s_{rc} =$	120	72.80	1751.30	1709.16	39.80	2.34

INTERPRETATION OF THE RESULTS REGARDING TO THE SCALABILITY

Evaluation of the masses

The test specimens with a scaling factor of $\varphi = 1.00$ represent the reference size. Based on Equation (2), the scaling factor φ between the reference mass ($m_{reference}$, $\varphi = 1.00$) and the masses from the scaled experiments (m_{scaled}) can be determined from the measured masses. The corresponding results and the expected scaling factors ($\varphi_{expected}$) are summarised in Table 4.

$$\varphi = \sqrt[3]{\frac{m_{scaled}}{m_{referece}}} \tag{2}$$

It can be seen that the mass of the plates before and after the experiment show very well the expected scaling factor.

Now it was checked whether the outburst masses also reflected the scaling factor. It was found that regarding the scabbing resp. spalling masses m_{sc} and m_{sp}, this effect was not perfectly recognizable. Just some of the experiments depicted the initially chosen scaling factor. The partially large deviations can be explained by an inaccurate evaluation of the outbreak masses as a consequence of not in all cases the damaged concrete could be detached completely from the plate and subsequently weighted. Even small masses that were not taken into account in this way caused large deviations, especially if this occurred on both the reference and the considered scale.

Table 4: Main experimental parameters and main results.

label	φ			
	$m_{plate,1}$	$m_{plate,2}$	m_{sc}	m_{sp}
1.25 - 1	1.25	1.25	/	/
1.25 - 2	1.24	1.23	/	1.14
1.25 - 3	1.25	1.25	0.26	2.34
1.25 - 4	1.25	1.24	1.39	0.91
1.25 - 5	1.24	1.24	1.39	1.16
$\varphi_{expected}$ = 1.25				

label	φ			
	$m_{plate,1}$	$m_{plate,2}$	m_{sc}	m_{sp}
1.50 - 1	1.49	1.49	0.29	/
1.50 - 2	1.49	1.49	/	2.00
1.50 - 3	1.49	1.49	1.50	2.15
1.50 - 4	1.49	1.49	1.72	1.70
1.50 - 5	1.48	1.47	1.94	1.87
$\varphi_{expected}$ = 1.50				

Evaluation of the support forces and deformations

Figure 4 and Figure 5 show the measured and summed up support forces (Equation (3)) resp. displacements (Equation (4)) in the experiments over time. Additionally, the related graphs by using the scaling law are displayed. The scaled measured values are displayed in dotted lines. The respective maximum values are drawn as dash-dot lines.

$$\Sigma LC = \frac{\Sigma LC_{scaled}}{\varphi^2} \tag{3}$$

$$w_1 = \frac{w_{1,scaled}}{\varphi} \tag{4}$$

Looking at the Figures 4 and 5, it is recognizable, that the measured result variables can be compared well with the respective scaling factors. The graphs do not show an ideal match. However, it can be seen that the different test scales are linked to each other via the scaling factors.

In the graphs in Figure 4 and Figure 5, only the summed support force and the measured deformation were scaled and displayed. However, if the scaling law given in Table 1 is taken into account, it becomes clear that this is still not sufficient. The test time must also be scaled accordingly (see Table 1). This was done in Figure 6 by using Equation (5).

$$time = \frac{time_{scaled}}{\varphi} \tag{4}$$

The little unclear measurement data from Figure 4 and Figure 5 are now clearly more similar to each other. With a few exceptions, e.g., deformation at speed "1", the measured values, which are now also scaled in time, fit very well together.

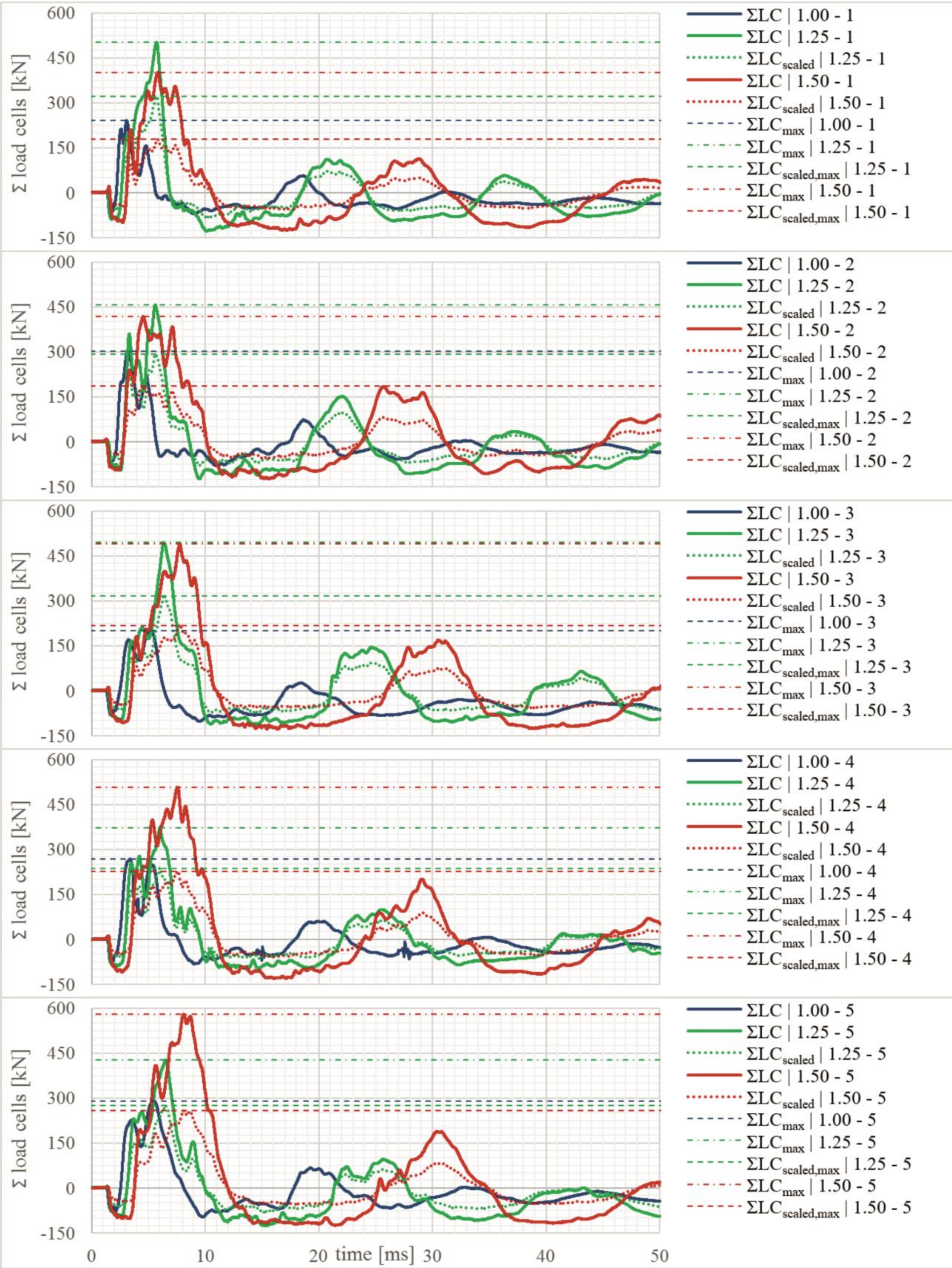

Figure 4. Evaluation of the measured support forces. Diagram: M. Hering

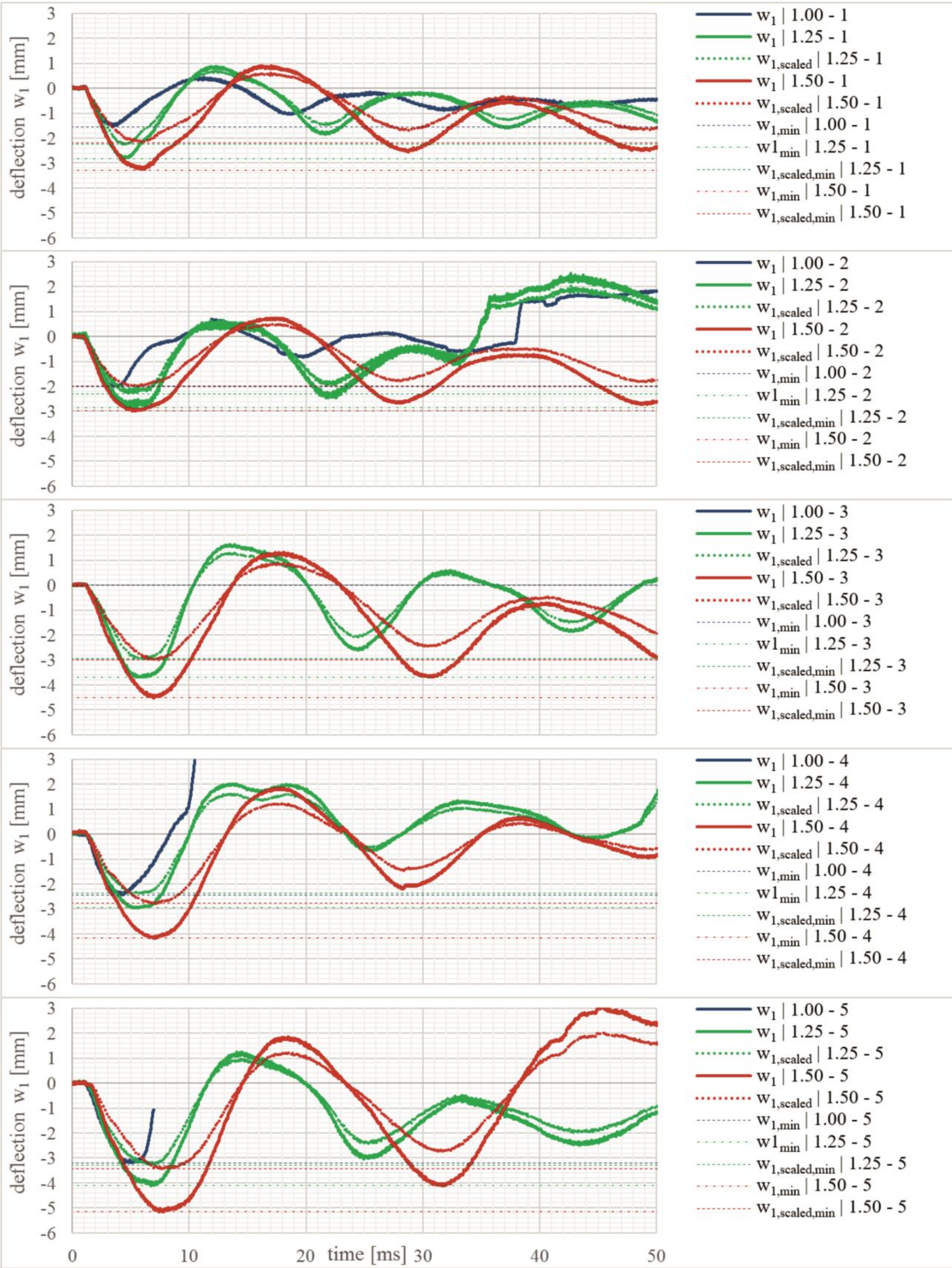

Figure 5. Evaluation of the measured deformation w_1. Diagram: M. Hering

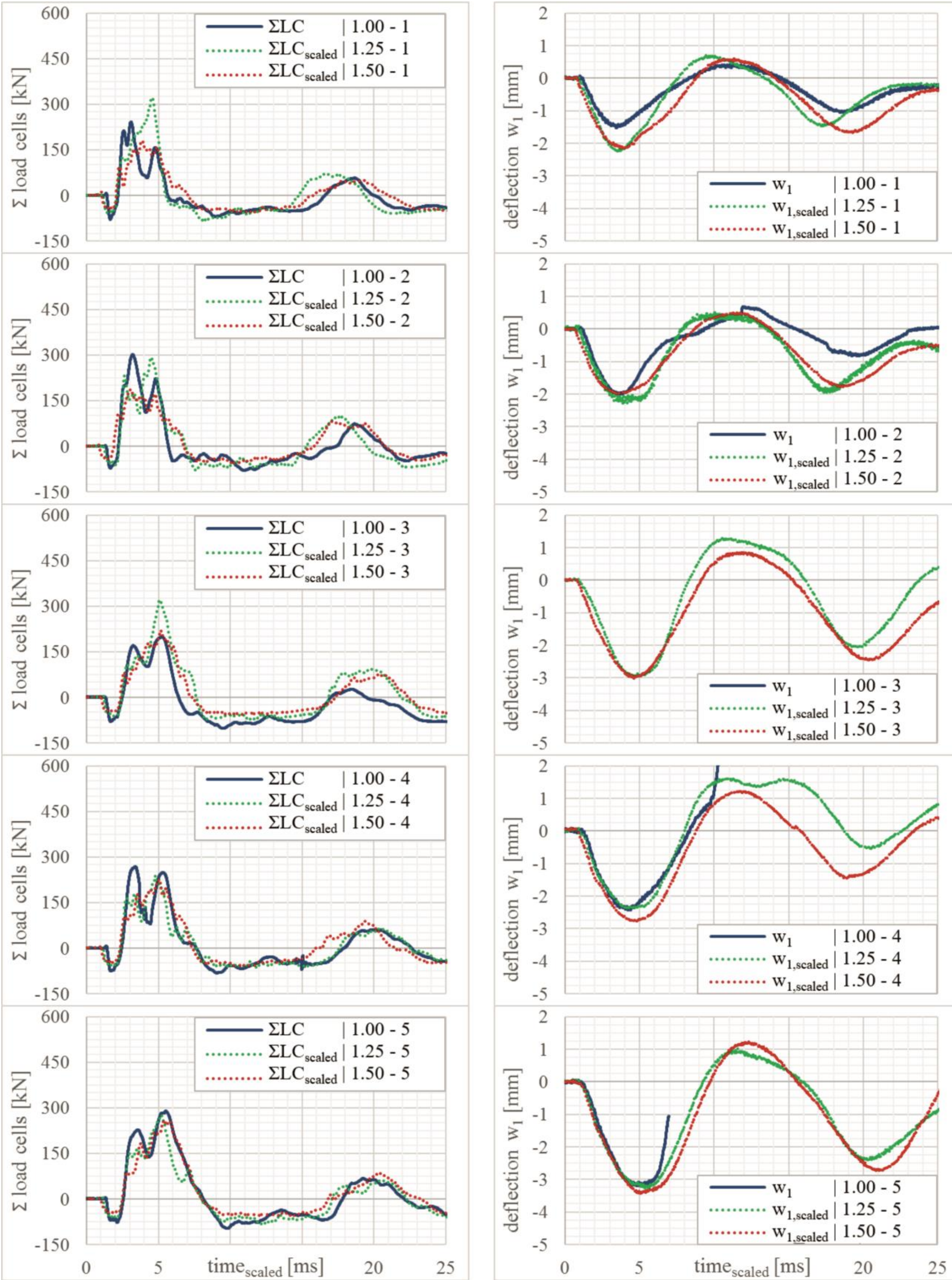

Figure 6. Plot of the scaled experimental results over the scaled time. Diagram: M. Hering

CONCLUSIONS

The experiments carried out on the scalability of impact experiments were able to show that the scaling law described in Sugano et al. [7] can also be applied to reinforced concrete plates. The results obtained from the experiments show very good agreement in terms of their scalability. However, it also showed that a consistent scaling of the experimental parameters is necessary to achieve the results. It can be concluded from this that it is possible to extrapolate from a scaled experimental dimension to a real dimension. However, it is important to ensure that all geometric parameters are scaled.

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