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DISCUSSION ON DATA EVALUATION OF TOMOGRAPHIC AND NUMERICAL RESULTS

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ABSTRACT

The contribution discusses the processing and analysis of data generated on two different ways of investigations for impact damage in reinforced concrete structures. Damage investigations are essential to determine type and characteristics of damage and thus the residual capacity. Damage describing data is generated using two different types of investigation, a non-destructive tomographic as well as numerical examination. Subsequently, data of both sources was merged and analysed. Within the research project "Behaviour of structural components during impact load conditions caused by aircraft fuel tank collision" reinforces concrete plates were damaged by impact loading, see Hering (2020). Afterwards the damaged specimens were investigated tomographically as well as numerically using several methods and models. Aim of the presented research work was to specify an objective comparability of numerical data with experimentally determined damage patterns and based on this, to establish a quantitative damage evaluation.

INTRODUCTION

Due to its ability to withstand both compression and tensile stressing, reinforced concrete (RC) is one of the most common structural materials used in diverse civil engineering applications. The wide variation of the physical properties still leads to an engineering challenge to develop prediction models for the determination of dynamic load effects on RC structures under impact or explosion loading. Structural safety gains public perception caused by a raising number of terroristic attacks and raising war thread. Therefore, it is necessary to increase the understanding of the performance of RC structural details under impact loading and so increase the operational safety of infrastructure buildings in more detail.

The demand to predict possible impact damage at RC structures was outlined with the first development of empirical formulas at the beginning of the 20th century. Since then, empirical descriptions have been investigated, extended and calibrated continuously. Li et al (2005) gives a general review on that subject.

Repeatedly, experiments have been carried out mostly on small scale to identify influencing parameters and to better characterize possible effects at the local impact area. For example, in Beppu et al. (2008), and Sadiq et al. (2014) projectile impact at velocities between 70 and500 m/s with varying boundary conditions was investigated. Large-scale investigations of projectile impact or aircraft impact are expensive and therefore less frequently performed, e.g., in Duan et al. (2018) and Saarenheimo et al. (2015), where large RC plates of different dimensions were tested with hard, soft and soft water-filled impactors. Both, small- and large-scale experiments have been numerically computed and evaluated, e.g. in Leppänen (2006) and Zhang et al. (2017).

The influence of the bar reinforcement as well as the stirrup reinforcement on the damage characteristics was examined, e.g., in Nerger et al. (2020b). Enhancing earlier research studies (Nerger et al. (2020a) and Nerger et al. (2020c)), the here presented investigations focus on further aspects, especially on the combination of the results of non-destructive tomographic testing with those of numerical simulations.

With the post-impact damage analysis used in the here presented study, the resulting damage is evaluated and characterized by means of internal and external damage patterns. Due to the complexity of the material, it is difficult to predict the damage. Such, among others, the influence of the load history and the bond between steel and concrete is significant. Information about cracks, their structure and volume, can be obtained using non-destructive damage detection methods. Cracks up to a size of 0.1mm (hairline cracks), were detected by planar tomographic examination, Nerger et al. (2020a).

With the increasing number of test specimens and the necessary increase of effectiveness, the compilation of a finite element model and its experimental verification were done in parallel to validate the capability of prediction of the numerical models and of the empirical formulas. The contribution shows studies of low-velocity impact and post-impact evaluation. It is structured into impact loading description followed by the illustration of the numerical and planar tomographic procedures for damage analysis. In the last section the damage characterization and prediction capabilities by a combination of both analysis procedures are discussed in detail.

IMPACT LOADING

For the experimental investigation of the structural behaviour of RC structures under impact loading, the drop tower facility at the Otto-Mohr-Laboratory of the Institute of Concrete Structures of Technical University Dresden, Germany was used. For this purpose, two configurations of the drop tower are available. First, the gravity mode to perform drop tests with a mass up to 2.5 t and a maximum velocity of 15 m/s. The facility provides a second mode, where the impactor is accelerated by compressed air for conducting experiments with impact velocities up to 160 m/s. In both configurations, different shaped impactors could be chosen. A detailed description of the impact loading facility is given in Hering et al. (2020).

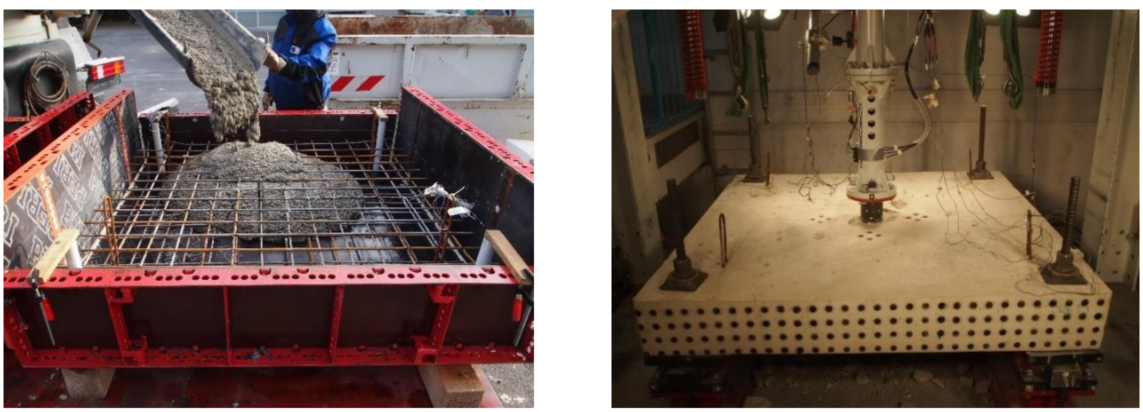

Figure 1. left: Manufacturing of the test specimen; right: Test setup of an accelerated impact test.

For all impact load tests RC plates with a quality of C35/45 and dimension of 1.5 m by 1.5 m were produced (see Figure 1 left). The reinforcement consisted of 8 mm steel rods and 100 mm spacing. The plate thickness varied within the performed test series between 10 cm and 30 cm.

For the investigations, presented here, the impact was generated with a cylindrical impactor with a diameter of 100 mm and a length of 380 mm. This leads to an impact mass of 21.66 kg. In general, the shape of the impactor nose has a strong influence on the local structural behaviour, for example the amount of spalling on the top and scabbing on the impact rear side. To achieve a local punching failure with a recognisable fracture body, a flat impactor nose was used. The test specimens were supported at each corner on a load cell which leads to four-point bearing conditions. The test setup of the impact experiments is shown on the right side in Figure 1 right.

PLANAR TOMOGRAPHIC INVESTIGATIONS

Non-destructive testing methods (NDT) are widely used to study and evaluate civil engineering structures. Depending on the required precision some methods become appropriate to visualize the internal structures of concrete specimens and to detect internal defects. Because of specific geometry of the plates under investigation in this research with depths up to 300 mm and a ratio of radiated thicknesses of 1:5 (300 mm : 1500 mm) a special type of tomography known as laminography was applied to determine the degree of the damage. Laminography is based on the relative motion of the X-ray source, the detector, and the object and allows to obtain spatial information on objects whose geometrical dimensions disallow measurements with computed tomography (CT) as for rotor blades or as in our case RC plates. Due to the dimensions of the plates, a scan regime of laminography called planar tomography was performed. Here, the emitter source and the detector are moved synchronized parallel to the object and the object remains fixed. The optimal scan regime includes four different horizontal and three different vertical positions of the emitter source and detector. Both are meandered horizontally and vertically while the object is stationary. At each single approached position, a scan takes place, consisting of 3 frames with an exposure time of 2 seconds.

Planar tomography measurements were performed at the High Energy X-Ray Lab (HEXYLab) located at Division 8.3 Radiological Methods of Bundesanstalt für Materialforschung und -prüfung, Germany (BAM). The manipulator provides 13 possible degrees of freedom (4 rotational and 9 linear axes) to determine the trajectories for the emitter source, the object and the detector which makes the investigation of complex geometries possible. The object to be examined can be up to 4 m long and 2 t in weight. The facility is presented in Figure 2 where the right side shows schematically the structure with the degrees of freedom.

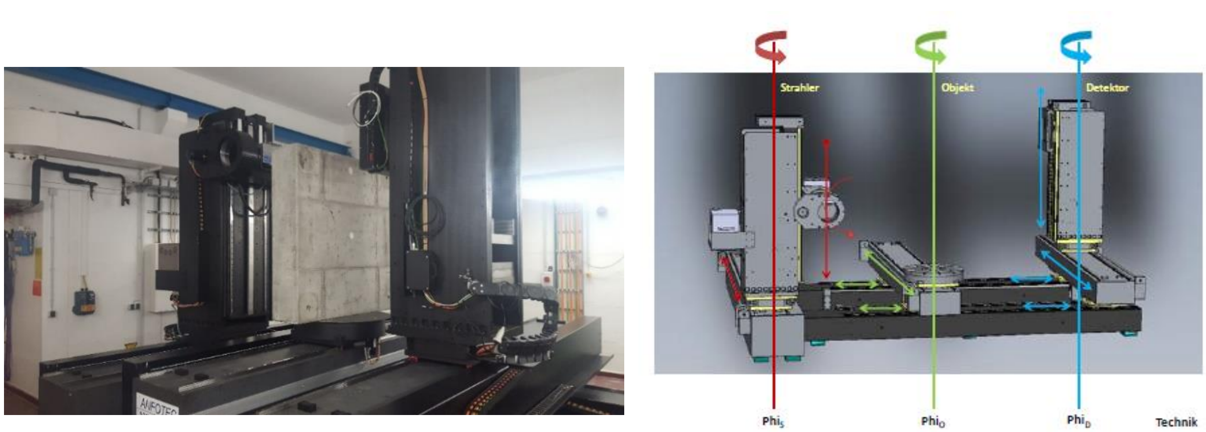

Figure 2. left: HEXYtech lab at BAM, Germany; right: Schematic structure of the components.

The reconstruction of the 2D projections was carried out using a fast shift-average reconstruction algorithm developed for the effective use of laminography. Like for the classical reconstruction algorithm, the computing time is approximately proportional to the product of the number of projections, the number of detector pixels and the number of calculated reconstruction slices. Detailed information about the tomography and the reconstruction algorithm can be found in Moosavi et al (2020).

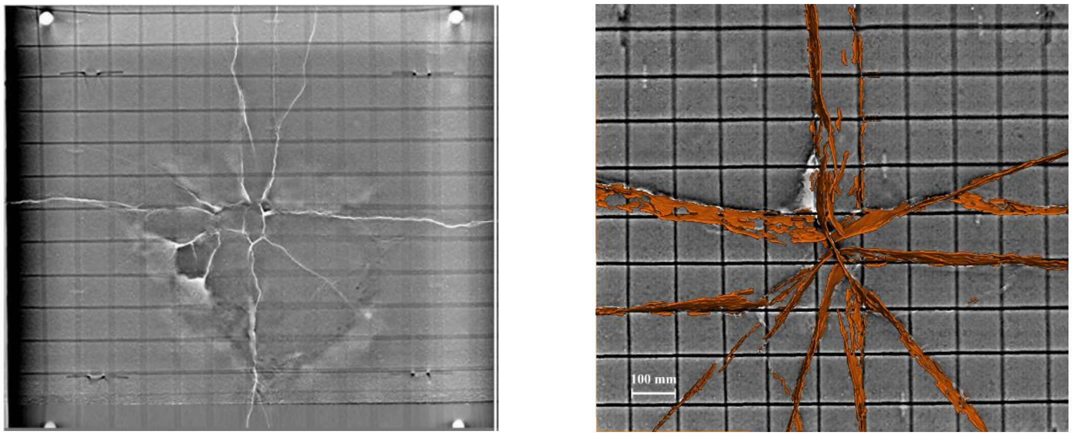

Figure 3. Results of tomographic investigation of impact damaged plates, at left a reconstructed layer and at right a 3D crack mapping (orange) into a 2D layer of row data (2-step algrorithm)

Up to 6.000 of max. 65.535 grey values are possible examining RC plates with a thickness of 300 mm. The number of possible grey values determines the contrast in the reconstruction. The higher the transmission (ratio of the grey values of the material to the grey values of the free beam), the better the contrast and the easier it is for the algorithm to detect cracks without the need for manual post-processing. Since the 3D data is not free of artefacts resulting from air inclusions, decreasing of the bonding between steel and concrete or from high-pass filtering, the detected cracks are not free of noises. Therefore, a two-step approach was applied which is briefly explained in Moosavi et al. (2020). In the first step, the reinforcement bars which cause artefacts in the crack detection are removed. To do this, a so-called tube templates are applied on the 3D data in order to find the tube-like reinforcements. In the second step, a crack detection algorithm which is also based on template matching method was applied on the data which is cleared out from reinforcements using the first step. Figure 3 shows on the left side exemplarily reconstructed 2D layer of an impact damaged RC plate. The right picture shows the 3D view of cracks detected by the two-step approach. The cracks are shown in orange and mapped in a 2D section of raw data.

NUMERICAL INVESTIGATIONS

Objective of the investigations on impact damaged RC plates is to predict the degree of damage in dependence of loading and structural circumstances and conditions. In addition to the experimental analysis for characterising damage effects a prognosis model was supposed to be developed. For the numerical simulations the commercial hydrocode ANSYS® AUTODYN was used. Within AUTODYN two already implemented material models for two concrete classes (C35 and C140) the Drucker-Prager model and the Riedel-Hiermaier-Thoma model are available.

The Drucker-Prager (DP) strength model is a two-parameter model in the three-axial stress space. In AUTODYN, the failure criterion is implemented in form of two combined failure surfaces for the pressure range and with the Rankine model for the tensile range. The body fails if one of the three principal stresses exceeds the tensile strength. With the help of triaxial tests, individual points of the curves could be defined, and the material model is completely described including the physical characteristics of the test specimen. The DP model does not include strain rate dependencies. Crack failure can be integrated with a specific module. Therefore, the fracture energy and the flow rule for the plasticity model must be specified.

With the Riedel-Hiermaier-Thoma model (RHT) the material behaviour is described by three failure surfaces, yielding and residual strength. In addition to the fracture criterion, two hydrodynamic equations of state (EOS) are included. They describe the compaction, as well as the porosity as a function of pressure. In case of high pressures and strain rates, a description with the EOS will be necessary. The RHT model describes the material behaviour using four physical parameters as well as 20 parameters for the fracture criterion and a total of 12 parameters for the two EOS strain rate effects in the tensile and compression range. Also hardening at high pressures and strains, softening due to shear damage and the coupling of damage due to pore collapse is used for description.

Both material models have their optimal range. The DP model can be used for static calculations without significant shear effects. On the other side, the RHT model is designed for high projectile velocities. In load cases where the projectile velocity is proportionally low and shear effects occur in the target, the material model must be well adapted.

Within the scope of the research numerical simulations from free-fall tests up to 10m/s, impact tests up to 100m/s and explosion tests (750g PETN) were performed. Exemplary, Figure 6 illustrates the simulation results with the comparison of numerical results with the tomography result data and the original photographic image of a RC plate damaged with a free-fall drop test. At top, the figure shows the superposition of the numerical determined damage with the tomographic data of the half plates back side. At bottom, the photographed cross section of the cut plate is compared with the numerical result. The plates damage was computed with both material models. The colour scheme of the damage result map ranges from blue (0% failure) via yellow to red (100% failure) to describe the failure probability of each finite element.

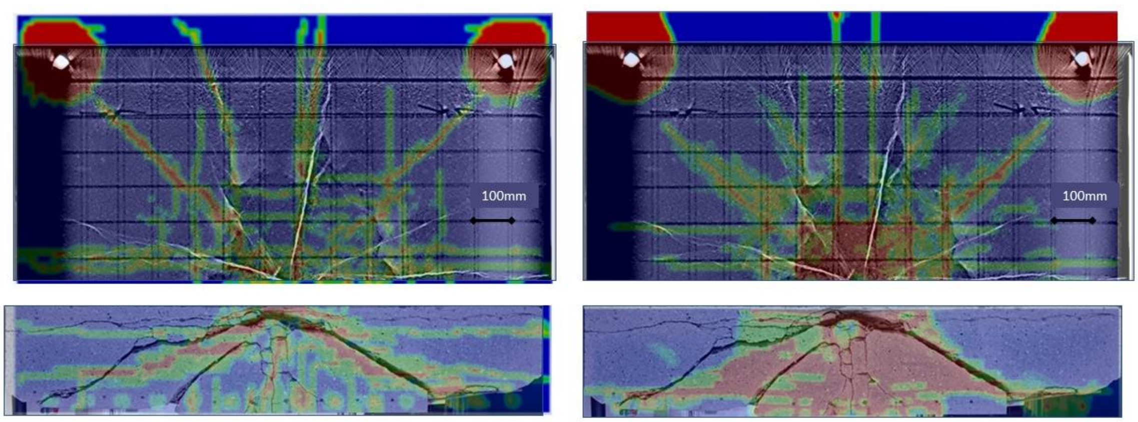

Figure 4. Results of numerical simulation at one RC plate, at right using the DP and at left the RHT material model. At top the backside of an impact loaded plate and at bottom the cross section.

With this comparison the quality of the numerical simulations is objective. While the numerical material parameters are already well validated for free-fall tests, the quality of the results for impact tests strongly depends on the material describing parameters as well as on the plate thickness.

COMBINATION

Besides using both investigation procedures, tomographic and numeric, independently, the combination of both with the further inclusion of all selected information regarding impact damage, structural boundary conditions and the outer damage parameter was intended to characterize the impact damage best possible. Among other parameters, the combined damage analysis includes the crack angle, the crack volume, the crack width (maximum, average values), the crack depth (maximum, average values) and the crack surface.

One aspect of the analysis of damage characteristics is shown in an example of a plate from a free-fall drop test (impactor velocity 6 m/s, impactor impulse 3049 kg and impactor radius 50 mm). Figure 5 (left) shows the damage on the back side of the in halve cut plate. Cracks are marked in black and the boundary of the scabbing is marked in red. The superposition of the crack structures from tomography (black) and numerical simulation (transparent blue) is shown on the right side of Figure 5(right). The resolution of the crack detection algorithm is 0.5 mm for one pixel in the plane and 1.5 mm per pixel perpendicular to the plane. That limits the automatic crack detection of hairline cracks and shear cracks. Therefore, the spalling, the punching cone and some oblique cracks are not visible in the crack detection.

Figure 5. Combination of damage characterizing information; at left cracks and scabbing on the back of half plate # P300; at right superposition of the crack structures from tomography and FEM

In Figure 6 the degree of damage of the cumulated crack damage with respect to the depth of the plate shows increasing damage until the midst of the plate (see Figure 13, left). Since the material has spalled off on the bottom fewer cracks can be detected and the values decrease at the end. In the case of the investigated plate the damage cumulated from cracks, spalling, scabbing and punching cone results in 2.84% of the total plate volume, whereas the damage due to the detected cracks amounts to 0.7%. The greatest damage occurs at a depth of 150-250mm and includes cracks with a depth of 100-150 mm.

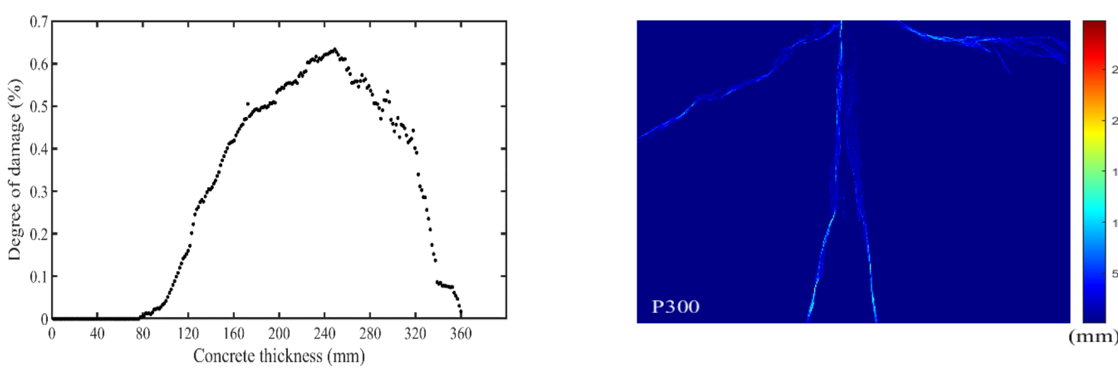

Figure 6. left: Degree of damage with respect to the depth of the investigated plate # P300 with an offset of 60 mm; right: Depth of the tomographically identified cracks of plate # P300

I was observed, that compared to free-fall drop test damage, the damage distribution with respect to the depth is different in accelerated drop tests. Figure 7 shows two 200 mm thick plates of different reinforcement properties where the damage increases with depth and has its maximum on the bottom, where most cracks and spalling occur. The cracks are finer and shorter in the accelerated drop test plates. The damage in the plate with stirrup reinforcement (# S37P06) is of a different nature. There are more deep cracks to be identified, whereas the area of spalling has a smaller diameter (Figure 7 bottom). The damage distribution along the depth (Figure 7 top) indicates a punching cone that has not yet detached compared to the plate without stirrup reinforcement (# S26P01).

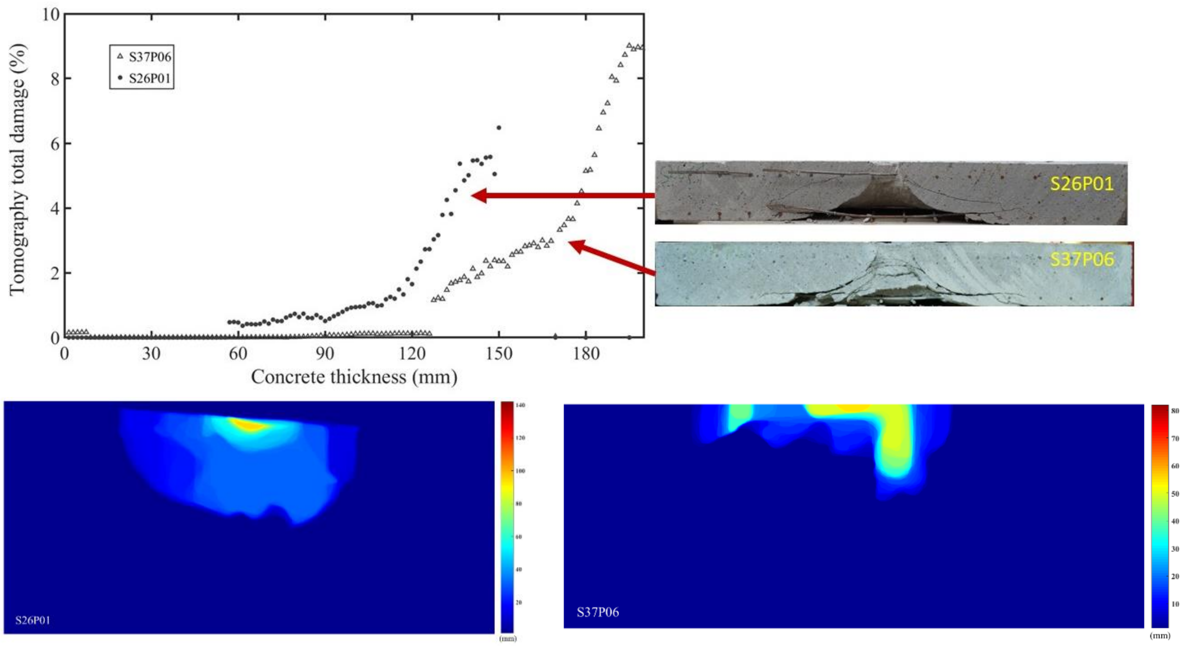

Figure 7: top: Degree of damage with respect to the depth of the investigated plates # S26P01 (without stirrup) and # S37P06 (with stirrup); bottom: Depth of the tomographically identified spalling

CONCLUSION

In this contribution, impact damage experiments on RC plates with different impact velocities, plate thicknesses and reinforcement configurations were presented. The effects of local damage were analysed and characterised.

Numerical simulation is a useful tool for creating a prognosis model of the damage characteristics. Superpositions of FEM, photographic images of the plates and tomographic data indicate similar damage characterization. The simulations thus give the possibility to carry out further investigations and parameter studies on RC structures.

After adaptation of the crack detection algorithms, the plates were examined planar tomographically. The refined and optimised algorithm was presented. For a direct comparison of the damage structure from the tomographic investigation with that from the numerical simulations, the image processing of the crack structures and spalling was binarized. A more detailed analysis of the cracks was performed based on crack widths, depths and volumes.

Besides the individual consideration of the testifies of the tomographically as well as numerically investigations the combination of results from both, enriched with information from loading as well as from the structural characteristics lead to quite comprehensive evidence about the damage states. This diagnostic information will help to improve the understanding of dependencies between several outside loading and inside structural parameters, and further will help to improve and refine modeling and computing parameters for large scale numeric simulation based predictions of impact damage.

Based on the described investigations and on the presented results further studies will follow, focussing the possibilities of transferring results and testifies into large scale and real dimensional task assignments. Of particular interest will be the characterization of the crack structures in the comprehensive damage pattern and their influence on the penetration behaviour of fluids.

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