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MINERAL-BONDED COMPOSITES FOR ENHANCED STRUCTURAL IMPACT SAFETY – OVERVIEW OF THE FORMAT, GOALS AND ACHIEVEMENTS OF THE RESEARCH TRAINING GROUP GRK 2250

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Abstract: Existing concrete and reinforced concrete structures feature, as a rule, a relatively low resistance against various types of dynamic loading, such as earthquake, impact or blast. This makes it important to develop effective and feasible solutions for the enhancement of the structural impact resistance, for example, by applying thin layers of strengthening material. In the frame of the Research Training Group GRK 2250 "Mineral-bonded composites for enhanced structural impact safety", established in 2017 by the German Research Foundation (DFG) at the TU Dresden, design concepts for such strengthening layers are developed and investigated experimentally and numerically. The contribution provides an overview about the goals, structure and multidisciplinary research done by the Research Training Group and presents some representative results on the impact resistance of ductile composites with continuous textile and/or short fiber reinforcement.

1. INTRODUCTION

Concrete is by far the most widely used construction material in modern infrastructure and buildings. However, due to its brittle behavior, concrete is vulnerable to dynamic loading. The low impact resistance of reinforced concrete structures often leads to dramatic consequences in case of traffic accidents, earthquakes, rockslides or terrorist attacks. Considering the high involved social, economic and ecologic risks, strengthening concepts need to be developed for increasing the impact safety of the critical infrastructure.

In view of the high relevance and urgency of the problem as well as the wide range of engineering and social aspects to be taken into account, TU Dresden has formed the multi-disciplinary Research Training Group 2250 [1]. The goal of this project, funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), is to develop new materials and design approaches for the strengthening of existing jeopardized concrete structures.

The proposed strengthening concept is presented in Figure 1. It suggests the application of thin layers of novel, mineral-bonded fiber reinforced composites, such as Textile Reinforced Concrete (TRC) [2,3] and Strain-Hardening Cement-based Composites (SHCC) [4,5]. These materials exhibit a high tensile ductility, mechanical strength and durability, and can be applied in thin layers by using various efficient techniques, such as laminating or spraying [6].

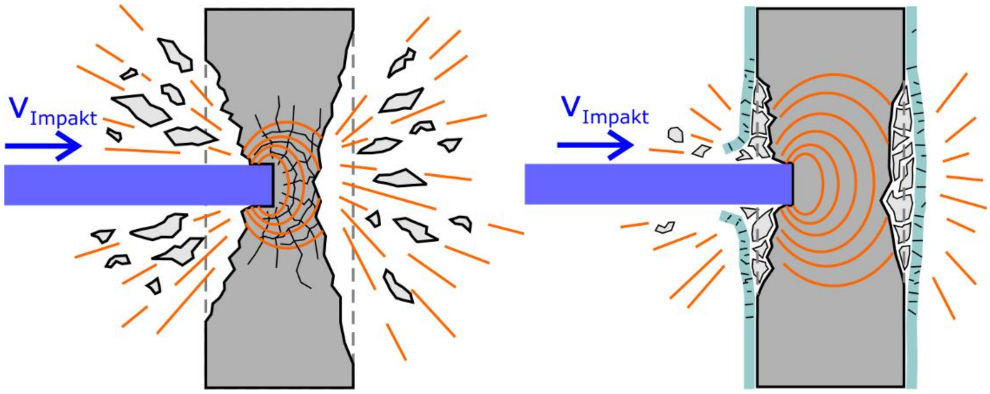

Figure 1. Behavior under impact of an unprotected concrete element (left) and of a concrete element strengthened with ductile mineral-bonded composites (right). Graphic by Marko Butler.

The paper will briefly present the format of the Research Training Group, its main goals as well as the main achievements after two years of project duration.

2. SPECIFICS OF THE PROJECT

The complexity of the subject, the wide range of involved phenomena at different scales of observation as well as the related economic and social aspects require a multi-disciplinary approach and, consequently, a team with different research profiles. This strategy was implemented in the form of a Research Training Group (GRK), a special format created and sponsored by the German Research Foundation. Research Training Groups represent collaborative national or international projects on specific topics, but with a pronounced multi-disciplinary character. Strong emphasis is put on the synergetic cooperation among the GRK researchers/doctoral subprojects. The young researchers involved in a Research Training Group are committed to following a PhD qualification program and to completing their projects within three years.

GRK 2250 was established in May 2017 and is planned for three consecutive periods (cohorts) each of three years duration. The first cohort (GRK 2250/1) involves directly twelve PhD students, one postdoc and twelve associated members (colleagues involved in other projects but working on related topics). The principal investigators supervising the cohort belong to nine different departments and four different faculties of the TU Dresden plus to the Leibniz Institute of Polymer Research, IPF Dresden [6]. The main research profiles of the GRK 2220/1 members are textile technology, polymer and material science, construction materials, structural engineering, continuum mechanics, numerical modelling, 3D optical monitoring techniques as well as sustainability and resilience. The broad spectrum of profiles is aimed at extensively covering the subject of the project from the micro-scale to the structural scale experimentally and numerically, and to facilitate a strong synergy among the subprojects. The GRK 2250 is coordinated by the Institute of Construction Materials with the first author of this article being the postdoc and the second author the speaker of the Research Training Group.

For promoting fruitful interactions within the GRK as well as for supporting the completion of the PhD projects within the prescribed period, the Research Training Group follows a well-structured qualification program. The PhD students organize regularly literature and research seminars, in which they present their progress and summarize relevant literature studies. Workshops and summer schools are organized every winter and every summer semester. There, the PhD students present their latest results, report on the visited lectures and give their feedback to the supervisors on organizational and research aspects in the project. International top scientists from various relevant fields of expertize are invited to attend these events, to provide their opinions on the research work presented as well as to deliver lectures and consultations. Upon agreement, they can take over the co-supervision of some GRK PhD students and/or host them at their institutions in the framework of a research visit.

In addition to conducting their research stays with an international tutor, the students are encouraged to participate at conferences to present their research for better integration into the research community, and to attend various scientific and soft skills trainings in order to improve their overall qualification.

3. GOALS AND FRAMEWORK

The main goals of GRK 2250 can be summarized as follows:

- Development of new impact-resistant mineral-bonded composites, i.e. fine-grained concretes with different types of fiber reinforcement, both for the front and rear sides of impacted concrete elements;
- Targeted development of the reinforcement and adjustment of the reinforcement-matrix interaction for the best performance of the composites;
- Development of design concepts and guidelines for the strengthening of existing concrete structures through thin layers of novel, highly ductile composites and for the construction of new structures using these new types of concrete;
- Development of appropriate testing and evaluation methods of the processes occurring during impact, such as wave propagation, deformation, fracture, etc.;
- Development of methods for the numerical simulation of the behavior of novel types of cement-based composites and strengthened structures subject to impact by coupling different space and time scales;
- Defining criteria for safety and performance evaluation and implementing sustainability and resilience criteria early in the design process.

The framework of the first GRK 2250 cohort is presented in Figure 2. Six PhD projects (highlighted in blue) cover experimental topics, four projects deal with numerical simulations (orange), while two projects (green) cover metrological and empirical subjects, respectively. A more detailed description of the research concept is given in the next section.

4. OVERVIEW OF THE RESEARCH

4.1. Reinforcement design

Since the continuous and short-fiber reinforcements play an essential role in achieving the desired composite behavior, these constituents must be tailored accordingly.

Project A1 deals with the design and production technology of continuous textile reinforcement. The design process is partly iterative and takes into account the results obtained in the experimental projects on the material and structural levels. Various 2D textiles made of carbon and polymer multi-filament yarns are part of the research program, but the main scientific goal of the project is the design of 3D cellular reinforcement made of metal wires and the development of an automated production process for such a reinforcement [7].

The discrete fiber reinforcement is needed for a micro-scale confinement of the cementitious matrix, in this way allowing a better crack control, higher energy dissipation capacity and avoiding spalling/scabbing effects during highly dynamic loading. In the project A2, polymer and glass micro-fibers are designed, produced and surface modified aiming a favorable crack bridging behavior in cementitious matrices.

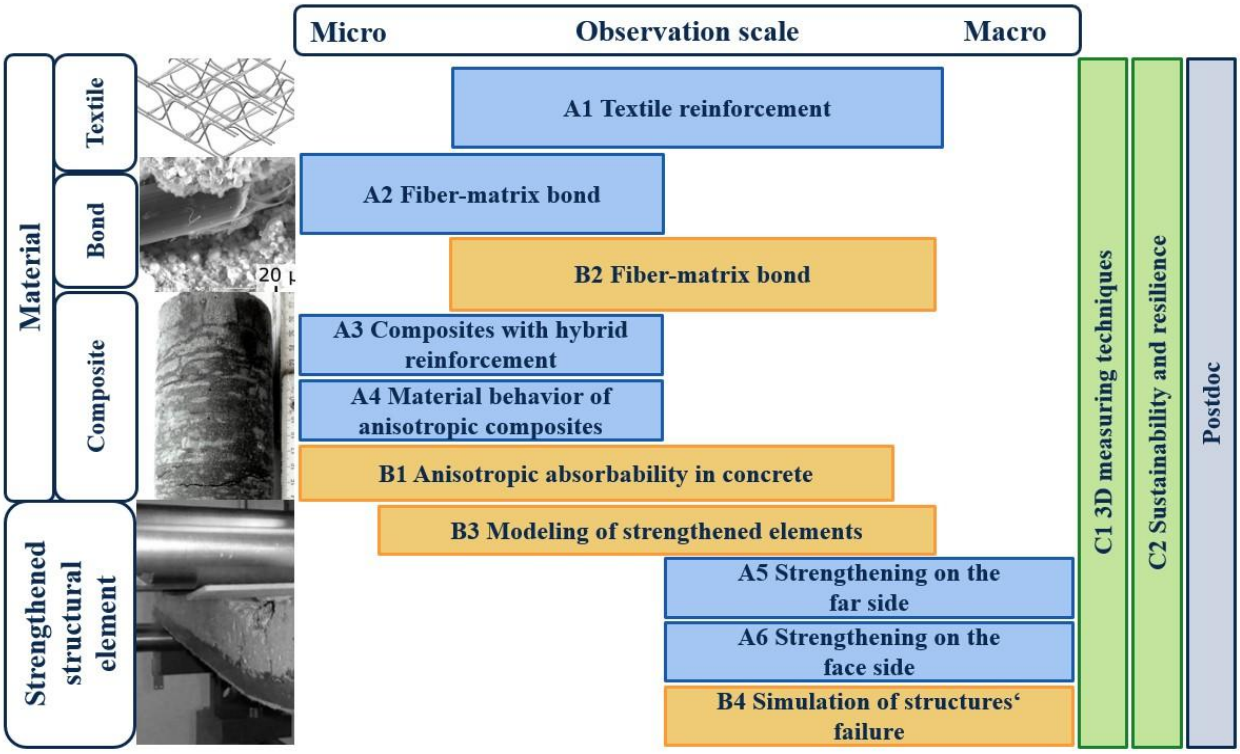

Figure 2: Framework of the Research Training Group GRK 2250/1. Graphic by Marko Butler.

The mechanical and surface properties of the fibers, the resulting fiber-matrix interactions and the corresponding strain rate effects are assessed in analytical and micromechanical investigations [8-10].

4.2. Material design, testing and modelling

The conceptual material basis for the project is represented by SHCC and TRC. For the purpose of structural strengthening against severe dynamic actions, the application of thin layers combining both reinforcing principles is highly promising. The role of the textile reinforcement is to ensure a strong confinement of the strengthened element as well as to distribute the local mechanical action and avoid premature failure localization. The randomly distributed micro-fiber reinforcement should increase the cracking stress of the matrix, enhance the crack control and reduce the extent of spalling. However, the favorable synergetic effect of the short and continuous reinforcements is not trivial and requires a purposeful material design based on a clear understanding of the mechanical interactions in the composite.

The synergetic combination of continuous textile and short fiber reinforcement in impact resistant cementitious composites is the goal of the project A3. The mutual influence of these two reinforcement types as well as the governing mechanisms influencing the behavior of the composites under quasi-static and impact tensile loading are identified experimentally and used as basis for multi-scale analytical modeling and for formulating performance-based material design concepts [11,12].

The impact experiments in A3 are performed in close cooperation with project A4, which designs and sets up dedicated high-speed material testing systems [13,14]. Additionally, the project aims at achieving a sound experimental linking of different scales of observation. For this purpose, the dynamic events expected at structural level are broken down into primary loading modes, i.e. tension, compression and shear, and reproduced at the level of the composite materials and of their constituents.

The experimental evidence obtained in projects A2, A3 and A4 serves as input and as basis for model calibration and validation in the numerical projects.

The goal of the project B1 is the formulation of a consistent two-scale homogenization framework using the FE²-method to simulate SHCC under impact loading [15]. To describe the mechanical behavior of SHCC at the mesoscale, the discrete microstructure is taken into account including inertia forces. This should enable the coupled analysis of dynamic problems at the material and structural levels, while the results should also support other projects at different scales of observation.

The numerical project B2 aims at modelling SHCC with a discrete, one-dimensional representation of randomly distributed short fibers [16-18]. In the simulations, the Strong Discontinuity Approach (SDA) is considered for continuum, and truss elements are embedded in the continuum with flexible bond. This approach allows a detailed analysis of the composite behavior under various loading conditions and speeds with regard to material composition, morphology and micro-mechanical properties.

The project B3 models textile reinforced concrete with an explicit representation of the textile yarns. The goal is to develop and apply homogenization techniques for enabling a multi-scale analysis under static and transient loading scenarios, as well as to define representative volume elements for an accurate but efficient simulation of textile reinforced layers at the structural scale [19].

4.3. Structural strengthening

The strengthening layers must yield different energy dissipation mechanisms depending on their location relative to the area of load application. The goal of the projects A5 and A6 is to assess the performance of various strengthening concepts for the impacted and for the rear sides of structural elements, respectively. The experiments are carried out in an advanced drop tower facility [20-22]. Besides the quantitative and empirical evaluation of the performance of the concrete plates and strengthening layers, analytical and numerical simulations are performed for quantifying the inherent dynamic effects and deriving the material related parameters both of the RC plates and of the strengthening layers under high-speed impact loading.

The impact experiments on non-strengthened RC elements are modeled in detail in the project B4, in which an appropriate variational fracture scheme and a constitutive relation for concrete considering rate effects is developed in the framework of Finite Element Method (FEM). The goal of the project is to describe the structural failure under impact loading realistically and efficiently [23-26]. The outcomes of the projects B3 and B4 form the basis for the numerical simulation of strengthened RC elements.

4.4. Interdisciplinary projects

The highly dynamic experiments performed at material and structural levels require adequate 3D monitoring techniques. Furthermore, the specific behavior of the investigated brittle-matrix composites necessitates dedicated strain evaluation approaches, which facilitate an accurate quantification of the cracking and fracture processes. These aspects are addressed in the project C1, in which algorithms are developed for an automatic strain and crack pattern quantification under various loading speeds and on surfaces with different geometric properties [27,28]. These developments do not only directly support the experimental projects, but are also used for verification and validation purposes in the numerical simulations.

The project C2 addresses the resilience and sustainability of the developed strengthening solutions. Besides performing these assessments already during the development stage, the project triggers a certain awareness among the engineering colleagues with respect to the economic, ecological and social impacts of their works [29].

The role of the postdoc is to stimulate the synergetic cooperation and to establish a framework for an effective communication and information exchange among the members of the GRK 2250. Besides actively participating in the collaborative research, the postdoctoral researcher formulates and handles own interdisciplinary but self-reliant research tasks with the aim of developing comprehensive design and implementation concepts of impact resistant strengthening materials.

5. REPRESENTATIVE RESULTS

Although extensively studied at the material level [5,30,31,32] and in small-scale impact tests [20,33] the performance of SHCC and TRC as strengthening layers subject to highly dynamic loading conditions was not investigated as of yet. For getting an initial insight into the behavior of these materials as strengthening layers on the rear-side of impacted concrete elements, large-scale impact experiments have been performed involving well-studied SHCC and TRC compositions.

5.1. Structural testing configuration

The experiments were carried out in a drop tower facility, developed and assembled at the Institute of Concrete Structures of TU Dresden [20,21]. The drop tower can operate in a gravitational mode with a 2.5 tones drop weight, as well as by accelerating up to 100 kg heavy projectiles using air pressure [21,34].

The testing configuration adopted for the tests briefly described in this paper was the accelerated mode. With this facility, projectile velocities of up to 150 m/s using a charging pressure of 16 bar are theoretically possible. Among the various possible projectile geometries [21], the flat-head projectile was chosen for the current study.

Same as the impact velocity, the thickness of the RC plates represents a parameter under investigation for understanding the structural behavior. The in-plane dimensions of the tested large-scale RC plates are 1.5 m x 1.5 m, while the thickness varies between 10 cm, 20 cm and 30 cm [34,35]. The plates have two layers of steel reinforcement on the top and bottom sides consisting of 8 mm-thick rebars spaced at 10 cm in both directions. The concrete strength class is C35/45.

The plates are pin supported at the four corners. The projectile is accelerated towards the center of the plate, while the reaction forces are measured at the supports. Additional measurements are performed optically from the top and laterally for subsequent DIC analysis as well as using a laser sensor at the bottom and strain gauges on the steel rebars. Details regarding the control unit and monitoring systems of the setup may be found in [21].

The results presented here refer to the rear-side of an impacted element. To ensure a strong bond with the strengthening layer, the concrete plates' surfaces to be strengthened had to be prepared with a sufficient roughness (aggregates have to be exposed). The bond between substrate and strengthening layer is an important parameter on its own, but it was not a matter of main interest in the tests performed. The RC plates were strengthened at an age of more than 8 months and the thickness of the strengthening layers was 20 mm. The layer thickness is also a parameter to be varied in future tests.

5.2. Strengthening materials

The tensile behavior of the composites used as strengthening layers with and without carbon textile reinforcement are described in [11,12]. A high-strength SHCC made with 2% by volume of 6 mm long Dyneema SK62 fibers was used as reference strengthening material [31]. The tensile strength of this SHCC ranges between 6 MPa and 9 MPa, measured on 40 mm wide and 250 mm long specimens with a thickness of 20 mm. The strain capacity up to peak load bearing capacity ranges between 1.5 and 3%.

In the case of the hybrid fiber reinforced composites, a carbon textile TUDALIT-BZT2-V.FRAAS (manufacturer's code SITgrid 008) produced by V.Fraas GmbH was used. The carbon mesh is two-dimensional with rectangular grid-cells of 12.7 mm in the stronger (warp) direction and 16 mm in the weaker (weft) direction. The primary and secondary directions are not only determined by the yarn spacing but also by the yarn's cross-sections. The warp yarns have an effective cross-section area of 1.83 mm^2 with 48,000 filaments, while the cross-section of the weft yarns is 0.45 mm^2 with 12,000 filaments. The nominal tensile strength of the carbon textile in both directions is 1700 MPa. The Young's modulus in the warp direction is 170 GPa and 152 GPa in the weft direction [36]. Uniaxial tension tests performed by the authors have shown that the elongation capacity of the textile yarns is approximately 1.5%, a value comparable to that of the SHCC [12].

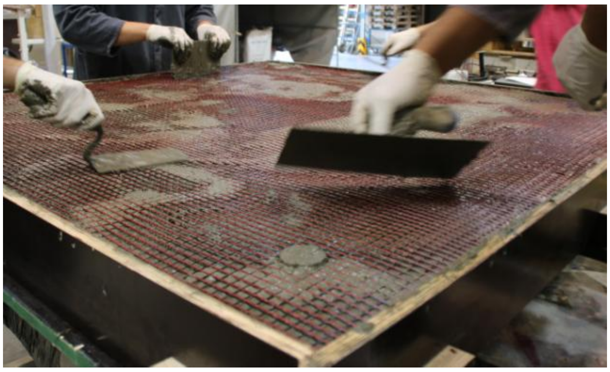

Figure 3: Application of the strengthening layer consisting of high-strength SHCC and two layers of carbon textile reinforcement. Photo by Ting Gong.

For the strengthening of the RC plates with layers of 2 cm thickness, 50 dm^3 of SHCC were necessary. The raw materials were mixed in a 60 liter capacity, high intensity Eirich mixer in consecutive batches of 25 dm^3 in order to ensure a high mixing intensity and proper fiber dispersion. Figure 3 shows the horizontal application procedure of the strengthening layers with hybrid fiber reinforcement. Two layers of carbon textile were applied with the yarns parallel to the plate's edges. The textiles were rotated 90° relative to each other to ensure the same reinforcement ratio in both directions.

The strengthening layers were cured under semi-sealed laboratory conditions (covered with wet towels) for 4 days, and subsequently stored outdoors for 23 days.

5.3. Strengthening performance of the applied materials

Figure 4 presents the middle sections of three tested plates, which were cut in half for a clear visual demonstration of the damage extent. The top plate was a non-strengthened RC plate, the middle plate was strengthened with SHCC and two layers of carbon textile, while the bottom plate was strengthened just with a layer of SHCC.

The non-strengthened reference RC plates showed a pronounced damage with deep penetration of the projectile and, consequently, high displacement of the punching cone. At high impact speeds, the damage on the backside was not caused by bending but by scabbing as result of the reflection of the induced compressive wave. The scabbing on the backside occurred concurrently with the compaction of concrete under the penetrating projectile, which led to concrete crushing and rendered the steel reinforcement ineffective.

Under the given loading conditions, the SHCC cover alone is not sufficient to confine the concrete substrate and prevent scabbing. This can be partly traced back to the strong bond between the two materials, which leads to a localized loading in the SHCC layer along the edge of the cone, which did not enable the exploitation of SHCC's ductility.

However, the strengthening layer with hybrid fiber reinforcement was able to completely transfer and distribute the local action and offer enough confinement to avoid complete loss of structural integrity. The high-speed optical measurements showed a large elastic-plastic deformation of the strengthening layer. This is ensured by the high stiffness and strength of the reinforcing carbon yarns. The SHCC matrix showed no failure localization but just fine, well distributed cracks. These results emphasize the importance of a continuous reinforcement in the strengthening layers and indicate that the volume content of short micro-fibers can be optimized without significantly affecting the performance of the strengthening layers.

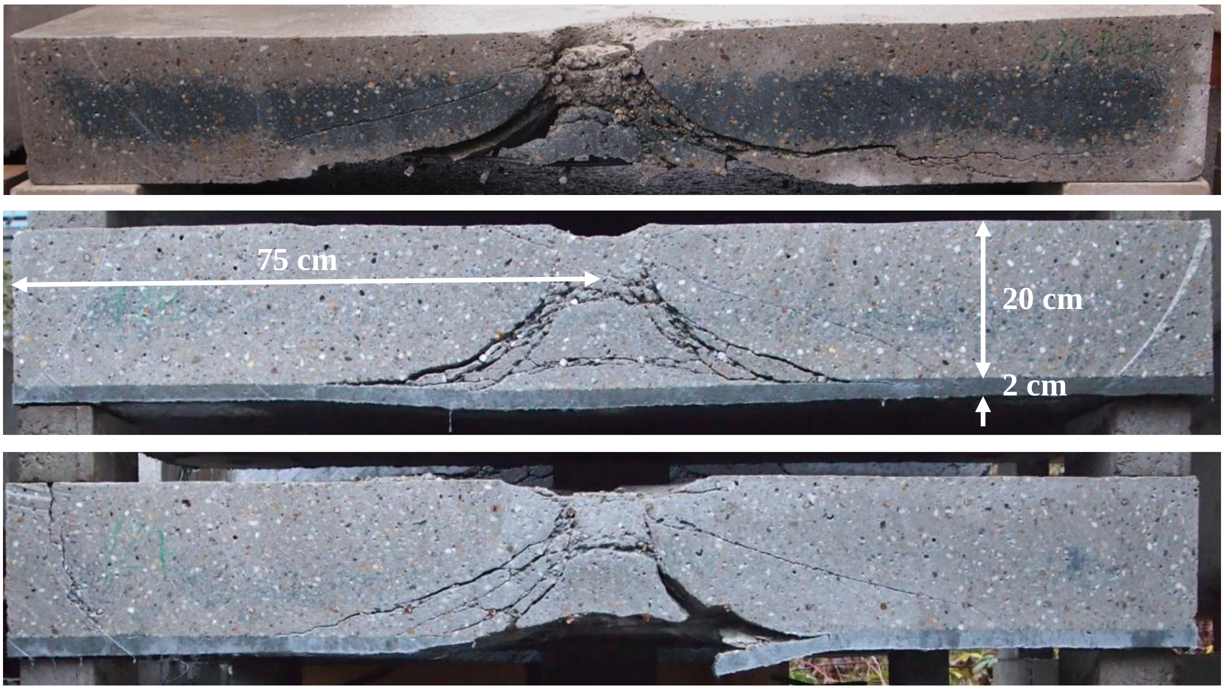

Figure 4: Reinforced concrete plates strengthened with different mineral-bonded composites on the rear side; upper plate had a hybrid fiber reinforcement, bottom plate: one layer of high-strength SHCC. After testing, the plates were cut through the middle for demonstrating the damage extent. Photos by Marcus Hering.

Based on the initial findings, the experimental testing at structural and material scales are shaped with regard to several important parameters, such as bond between substrate and strengthening layer, volume ratios of the discrete fiber reinforcement and textile reinforcement, etc. Furthermore, additionally to carbon, also textiles made of other materials such as ultra-high molecular weight polyethylene (UHMWPE) are investigated (in comparison to carbon this fiber has a higher tensile strength but a lower Young's modulus).

Furthermore, considering the high shear and compressive stresses induced on the impacted side as presented above, the design of the continuous reinforcement focuses on 3D-mesh structures, possibly made by combining different materials, e.g. steel and carbon, for efficiently bearing different fracture and crack opening modes.

6. SUMMARY AND OUTLOOK

Given the low damage tolerance and energy dissipation capacity of the most reinforced concrete structures, severe dynamic loading scenarios can yield dramatic consequences with high social and economic impacts. Thus, efficient and feasible strengthening solutions must be developed for the existing jeopardized critical infrastructure. In the framework of the Research Training Group GRK 2250, inter-disciplinary and multi-scale research is performed with the aim of developing impact resistant strengthening layers consisting of high-performance mineral-bonded composites with novel types of fiber reinforcement.

The research group brings together a wide range of competences and establishes a tight collaboration among the individual PhD projects. The research concept exhibits a hierarchic structure with respect to the scales of observation, i.e. from micro to macro, each level being covered by both experimental and numerical projects.

In the first phase of the GRK 2250, the fundamental mechanisms of the material and structural behavior under impact loading have been investigated, while the performance requirements have been formulated with respect to the strengthening layers on the front and rear sides of an impacted element. Based on these findings, appropriate strengthening materials have been developed, tested, and modeled at the levels of constituent materials and composites.

With project advancement, the goals and competences presented in the article at hand will be refined and extended. Such important aspects as durability and implementation technology will be additional topics of the future cohorts. More than that, the acquired knowledge and experience will allow generalizing the notion of “severe dynamic action” and consider other loading cases, such as blast.

The project is in a continuous interaction with numerous German and international research and academic institutions. The involvement of external partners has proved to be of an extremely high value for advancing with the goals and will be further promoted in the framework of the GRK 2250.

More information on the GRK 2250 can be found on the web page [1].

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