Dynamic Structural Behavior of Bridge Components under Explosive Effects

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Abstract

Critical transport infrastructure, such as tunnels and bridges, is designed to withstand a broad range of loading conditions. However, critical load-bearing members of these structures are typically visibly exposed or accessible, making them more vulnerable to terrorist attacks. Such structures therefore require special consideration and protection. Being able to predict the effects of explosions on structural integrity can aid both in determining conditions for safe usage and in developing proper protective countermeasures. Devising and applying techniques for quantitatively assessing residual load-bearing capacity of such structures when damage has occurred and what degree of damage constitutes critical damage is very important and is the focus of the described study.

In order to evaluate the criticality of different possible detonation scenarios, several components of physical structures are analyzed using various state-of-the-art methods. Reinforced concrete components under both contact and close-in detonation loading are examined using validated engineering tools. The presented evaluation processes enable thereby the definition of degree of criticality of different loading scenarios in relation to different reinforced concrete components. Global failure mechanisms are investigated by a combination of partly newly developed engineering tools, which facilitate a reliable appraisal for internal detonation scenarios.

For the bridge cables a stepwise analysis procedure including mesomechanical simulation of cables, scaled validation experiments and different types of prestress descriptions in finite-element simulations are presented. The observed influences on the response and extend of damage are highlighted. The above mentioned types of structures and components are not comparable to other types of critical infrastructure (embassies, administrations and ministries, high-rise buildings), which are built using reinforced concrete walls, columns and masonry. Therefore, they require new analysis and classification approaches, which are addressed and summarized in the proposed paper.

Keywords: Critical Infrastructure, Bridges, Detonation, Model Tests, Hydrocode Simulation, Bridge Cables

1. Introduction

As in many other modern societies, roads in Germany make up a crucial part of the national transport system and take the largest share in moving people and goods. They also play an indispensible role to other transport modalities such as shipping. The 2006 attempted attack against the Hohenzollern Bridge in Cologne shows that even Germany is not immune to acts of terrorism.

In order to better protect critical infrastructure, hazards must first be identified., The risk must then be analyzed in order to be able to give a quantitative assessment of the threat and to prescribe possible preventive measures.

An important step within this risk analysis consists of examining the degree of damage caused to individual structural components of, in this case, bridges and to the bridges themselves.

An all-hazard-approach identifying a wide range of threat scenarios against bridges and tunnels has been undertaken in the project SKRIBT (www.skribt.org). The demands on the structures, the user and the surroundings are considered, and counter-measures are being developed. With these demands in mind, the vulnerability to terrorist threats and the criticality of bridge structures are the focus of the described study.

To assess the possible threat of terrorist attacks against critical infrastructure, it is necessary to analyze the history of terrorist attacks. There are several databases containing terrorist events available in the internet. As the possibilities for analyses are limited to the available non-classified databases, a MS Access database was set up at the Fraunhofer Ernst-Mach-Institute (EMI). Publicly available data served as the basis for the in-house Terror Event Database (TED). To extract helpful information from TED, an analysis software was developed. This tool allows a fast filtration of the dataset. Descriptive statistics, time series analyses like trend analysis, cycle detection and comparison of time series are implemented within this tool. The analysis is based on three steps: data selection, method selection and visualization.

Figure 1 shows a percentage break-down of the tactics used in terrorist events against bridges and tunnels. The TED analysis has shown that most attacks occur with an explosive scenario. Hence, different explosive scenarios as decisive scenarios were chosen to investigate the vulnerability of bridges in case of terrorist attacks. A further result of the database evaluation was to determine the place on the building where the attacks can occur. Figure 1 shows also the places of the bridge prone to terrorist activities with explosive devices. For this reason, the investigation will focus on these locations.

By using the TED event analysis, different standard scenarios can be ascertained. The next step is to characterize the structure behavior in response to these scenarios. The estimation of each bridge component gives an answer to the criticality of each scenario.

Many relevant bridge constructions include pre- and non-prestressed reinforced concrete box-girders, steel box-girders and high-strength steel suspension cables. Here, the combined prestress loads in the MPa range and shock pressures of several GPa resulting from a blast differ by several orders of magnitude. This combination is a challenge for engineering and design principles.

In the presented study, the dynamic load-bearing behavior of each of these bridge components is first investigated individually. These results will serve as a basis for examining the dynamic response of a complex bridge assembly under blast loading. In all the accomplished investigations either by the means of experimental model tests or by the means of numerical simulations, the result is represented by a local degree of damage in the regarded bridge component or assembly. This local damage enables a classification and evaluation of the residual loading capacity of the bridge construction applying also several investigation methods, which are not presented in the paper.

In order to evaluate the criticality of different possible detonation scenarios in combination with the several components of infrastructural buildings mentioned above, various state-of-the-art methods in terms of model tests, engineering tools and finite methods are used and presented in the following sections.

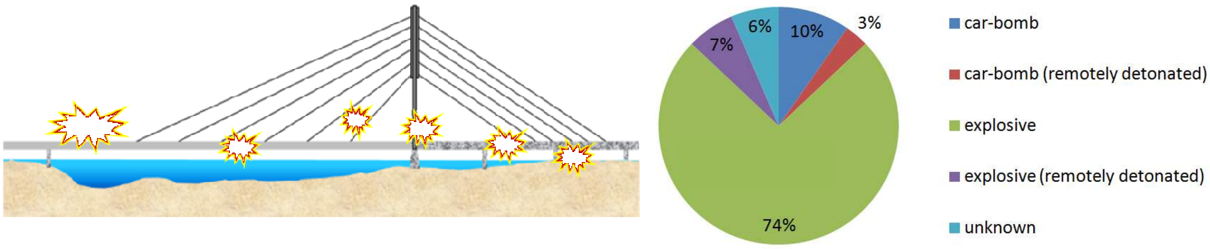

Fig. 1: Typical construction of a cable stayed Bridge in conjunction with possible detonation locations (left side)

Tactics against bridges and tunnels worldwide (right side)

2. Investigations of the Dynamic Response of Bridge Components under explosive effects

The sketch in Figure 1 shows a typical construction of a cable-stayed bridge. In addition to the bridge cables, the structure consists of reinforced concrete parts and several steel parts. In the following sections, the dynamic bearing behavior of these three kind of bridge components is analyzed precisely.

2.1 Local and Global Loading Cases on Steel Components

Before discussion of the reinforced concrete components in the following paragraphs, the steel components of a bridge construction will be the focus of the described investigations. Because of the large variety of the different steel alloys, no validated engineering tool is available to calculate the effects of the detonation scenarios on the steel construction elements. Due to the lack of availability of these tools, the dynamic bearing behavior of the examined component is analyzed using the well-established combination of numerical simulations and accompanied scaled model tests. All numerical simulations mentioned in this paper were done using a program code based on the finite method using finite-volume differences. The used code AUTODYN belongs to the class of the so-called hydrocodes.

After the successful validation of the simulations of the model test against the results of the experiments, the numerical model can be transferred to full-scale dimensions. In these full scale models, a profound prediction of the possible loading on the steel components of the bridge due to the various imaginable loading scenarios can be calculated.

Focus of this paper section is the research of the dynamic bearing behavior of the high-strength steel bridge cables. In a further section the dynamic behavior of normal-strength steel plate type construction elements is outlined.

2.1.1 Steel Bridge Cables

In the model tests, scale M1:10 to 1:50, a cold-drawn high-strength steel strand cable is stressed by a contact detonation. The Hopkinson-Cranz scaling law [1] is applied for cable as well as explosive charge to allow upscaling of the results to real bridge dimensions.

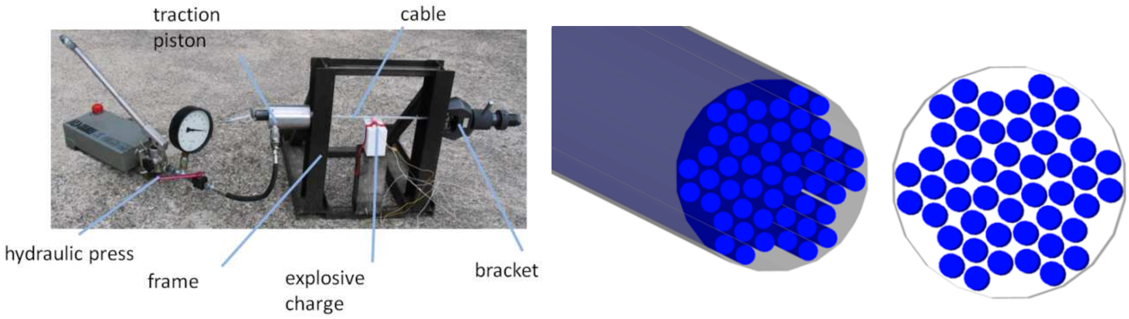

Fig. 3: Model test setup for prestressed and non prestressed bridge cables (left);
Associated mesomechanical numerical model for bridge cables (right)

The damage resulting from the detonation of the explosive is quantified by both analyzing the destructed wires of each strand and by determining the static residual strength in a tension test procedure. In contrast to other structural elements with a static preload, the prestress of the cables affects the degree of damage in a negative sense. In the model tests, a pre-stress of 30 % of the tensile strength, in turn, leads to a damage increase of about 30 %.A significant sensitivity on the geometrical placing of the explosive could also be identified in the model tests. This dependency results in the worst case in approximately 25 to 30 % more damage for the tested explosive quantities. The diagram in Figure 4 presents the results of the conducted model test series. In order to evaluate the reproducibility of the results, each defined loading scenario is tested several times. The derivation of these results is visualized in the diagram. To fill remaining gaps of a full-scale experimental analysis, numerical studies are also carried out. The expected damage to model-scale and full-scale bridge cables with different diameters and explosive masses can be calculated using finite-element simulations. The main characteristics of a steel-strand cable, such as the grade of steel, the stranding and fill factor of the cable therefore have to be modeled. Another important mechanical characteristic of a cable is the fact that its load-bearing capacity is limited to tension forces. Because cables in general are very slender constructions, with a high variety of constructions methods, the pre-assigned qualities are modeled by a mesomechanical approach presented in Figure 3.

The numerical model demands that several wires are simplified to one steel bar. In addition, the stranding of the rope is modeled by the combination of the frictional contact between strands are and the use of an outer shell with a thickness of one wire. . The steel components are characterized by the Johnson-Cook material strength model in combination with a shock equation of state. The strength model takes into account the temperature and strain-rate-dependent material strength and the non-linear kinematic hardening of the steel.

However, the fill factor and the steel grade correspond exactly to the modeled type of cable. Using this method, the depicted model configuration represents a compromise between numerical simplifications and correct reproduction of the rope phenomenology., For this reason, the quality of the numerical results is validated against the experimental data. In this validation, the influence of the chosen simplifications is analyzed by the use of a parametric study, which is also discussed in the following section.

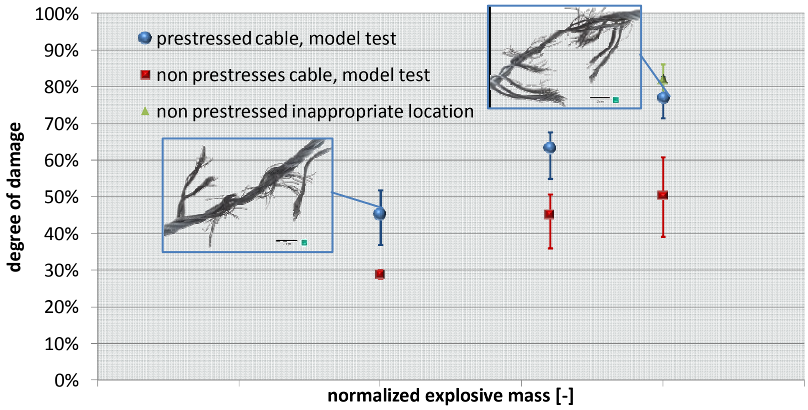

Fig. 4: Results of the model tests: measured degree of damage in terms of lost cross section in correlation to explosive mass, prestress and location

In the numerical model, each element row in cable lengthwise direction represents one wire of the modeled test cable. The number of cylindrical barrels in the numerical model corresponds exactly to the number of strands in the cable. By choosing this numerical composition and resolution, the degree of damage can be compared very precisely to the experimental results. The number of the destructed wires can be identified with this methodology as well as those, which are already plasticized due to the loading. In this way, the residual tension strength can be derived from the non-plasticized cables areas and can thereby also be compared with the experimental results.

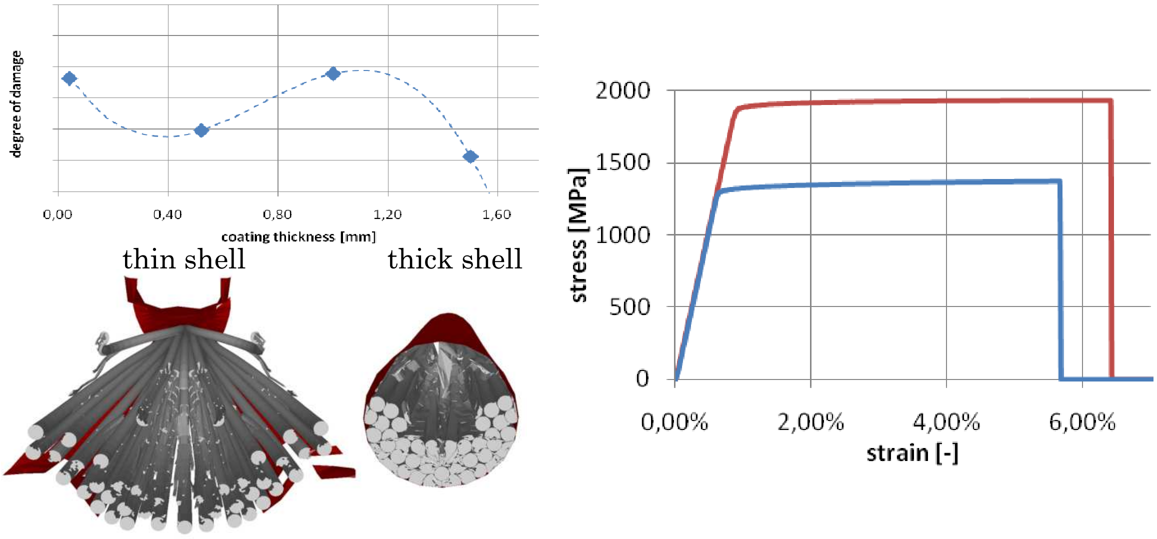

Fig. 5: Influence of the shell thickness on the calculated degree of damage (top left);

Deformation figure for a thin and a thick coat (bottom left);

Stress-Strain correlation for a prestessed (blue) and non prestressed (red) high-strength steel

The possible stranding of a cable is modeled, as mentioned before, by a combination of a frictional contact between the several barrels and the shell of these barrels.

In order to gather the effect of the friction coefficient, the same loading scenario was calculated with a friction coefficient μ = 0 compared to another simulation with a coefficient μ = 0.6. The observed deviation in the friction coefficient produces the slightly higher degree of damage. For this reason, all simulations were calculated using the friction coefficient 0.6, well knowing that this does not represent the physical steel to-steel-contact behavior. In fact, the friction coefficient represents the strand-to-strand frictional interaction.

Another simplification made in the numerical model by using the shell is to simulate the confinement of the strands resulting from the stranding. The thickness of this shell is set equal to the diameter of one cable wire, which enlaces the cables and serves as a conceptual construct.

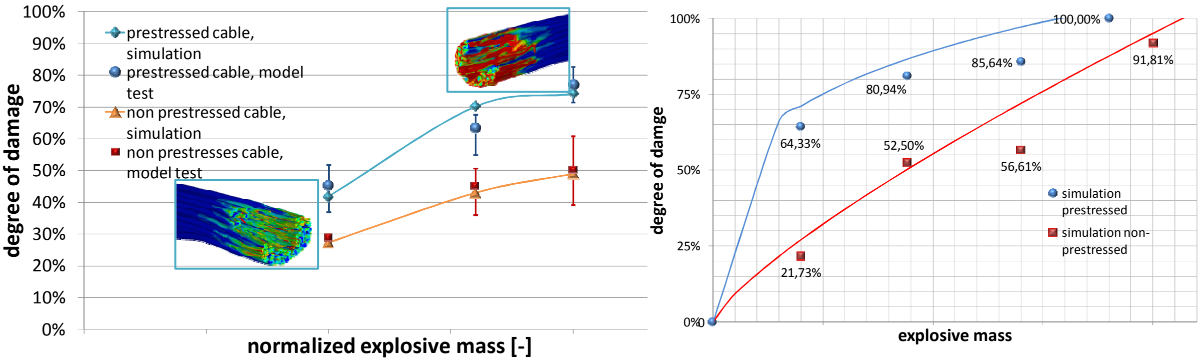

Fig. 6: Numerical calculated degree of damage in comparison to the experimental results (left)

Predicted degree of damage for prestresses and non-prestressed bridge cables in full scale

That this is a valid approach is underscored by the parametric study presented in Figure 5 (left-hand side). In the simulations with either no or only a very thin shell, the barrels spread out widely due to the loading. In contrast, the barrels with a thicker shell are confined in such a way that the deformation and the damage figure is very comparable to the experimental results. In addition, a further increase of the shell thickness decreases the calculated degree of damage which is not realistic and can lead to an unsafe design approach (see diagram in Figure 5).

Another point that was investigated in the numerical preliminary calculations was the approach to modeling the pretension in the prestressed cables. One alternative to modeling this pretension is to simulate both the direct and correct complete prestressing process. The numerical simulation of this process requires significant computational effort.

Another alternative to take into account the effect of the prestressing of the cable indirectly is the modification of the material stress-strain relationship in the material description of the high-strength steel. Due to the prestress, the elastic stress- strain-region of the cable is reduced, maintaining the stiffness of the cable. The difference between the prestressed and non prestressed material description is visualized in the diagram in Figure 5 (right-hand side).

Comparing the results of the direct method with the indirect method, it can be seen that similar results are calculated with the numerical models. Because the indirect method is computationally much more efficient, this method was chosen in all further simulations.

In the next step, the numerical results of the model and its previously discussed simplifications are validated against the experimental data.

The comparison in Figure 6 points out a very reasonable reproduction of the loss in cross -section for prestressed and stress-free cables – even if the deformation is not fully comparable to the experimental results due to the chosen modeling approach. Moreover, the dependency on the geometrical location of the explosive mass is also replicated in good agreement with the experimental observations.

A benefit of the model and its simplifications is the fact that it can be easily transferred to full-scale without any further assumptions. Because of the successful validation of the numerical model against the experimental data, the model can be transferred to the full-scale in order to calculate and evaluate the effects of different possible detonation scenarios. The diagram in Figure 6 shows the corresponding results. Analyzing both, the results of the model tests and the full-scale simulations, the degree of damage seems to be describable for both scales by a mathematical approach using a power function. In further ongoing investigations, it will be examined, if the degree of damage can be specified by a mathematical analytical power-function basing on the input parameters cable diameter, prestress level and explosive charge.

Nevertheless, with the presented numerical approach, it is now possible to predict and evaluate the degree of damage of a bridge cable, which is loaded by a detonation scenario.

2.1.2 Steel Plates

The model test set-up for steel plates, which is created in a scale M of 1:10, shows Figure 7. The steel plate is fixed on four-sides in a rigid steel frame. The clamp of the plate is applied in order to prevent a pull-out of the steel plate during the loading phase. The also scaled explosive charges are placed in the intended distance to the plate surface using a styrofoam spacer. Figure 7 (right side) visualizes the results of the test for a defined scenario.

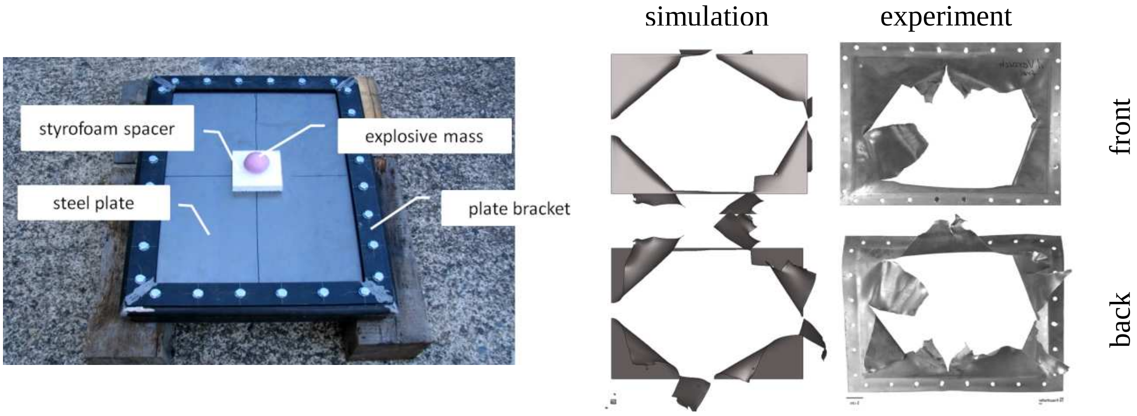

Fig. 7: Model test set up for the steel plates

Results of the experiments and the numerical simulation right for the front and backside

This model test set-up is simulated using again a finite element hydrocode. The comparison of the numerical results with the results of the simulations are presented in Figure 7, too. The size of the disrupted area arrived at by calculation is in very good agreement with the numerical simulation for both front side as well as the backside of the plate. Furthermore, the deformation figure of the plates is also computed in good agreement to the experiment. From this observation, it can be concluded that the numerical description of the dynamic steel behavior can be has been validated.

Summarizing, it can be diagnosed that with the presented numerical approach of normal-strength steel the effects on the steel components due to explosive effects can be predicted reliably. This can be done for several explosive charges at several arbitrary locations on the steel plate components.

2.2 Local and Global Loading Cases on Reinforced Concrete Components

Reinforced concrete components often constitute key elements in the bridge’s global load-bearing capacity. Because the dynamic analysis of reinforced concrete already regarded as astandardfield for the assessing building safety, the load-bearing behavior and capacity are already well understood [2],[3]. Consequently, simplified engineering approaches such as Single-Degree-of-Freedom models or empirical engineering formula can be used and are described in this section [4],[5],[6].

$$Z = \frac{R}{\sqrt[3]{W}} \qquad (1)$$

Construction components in general exhibit different response patterns, depending on the explosive loading intensity. Depending on charge weight W and separation distance R, local and global deformation modes such as critical bending or shearing of the structural component can be distinguished. The parameter of the scaled distance Z allows a differentiation between local and global loading according to equation 1. Small values induce shear loading, large scaled distances lead to a bending response [6].

In this paragraph, the focus will be on the carriageway slab, the columns and a reinforced concrete box-girder of a bridge. With respect to different explosive scenarios, the calculations predict the failure behavior of different structural elements.

Depending on the bridge construction, different categories of the carriageway slabs and different types of the columns have been investigated.

In the examination of each structural component, the critical value for the scaled distance was determined; for values smaller than the critical value, complete failure is expected.

It has been determined that for local loading cases, the percentage of reinforcement has only a minor influence on the structural resistance [7],[8]. But, in the case of global loading, the structure reacts by bending. Therefore, the percentage of reinforcement is essential for the structural resistance. With a higher percentage of reinforcement, the structure has a higher resistance against global loading cases.

2.2.1 Local Loading Cases on R/C Bridge Components

Contact or close-in detonations result in a deformation phenomenology, which is very complex. An extremely sharp shock front with pressures in the range of several Giga Pascal is transmitted from the explosive into the structure.

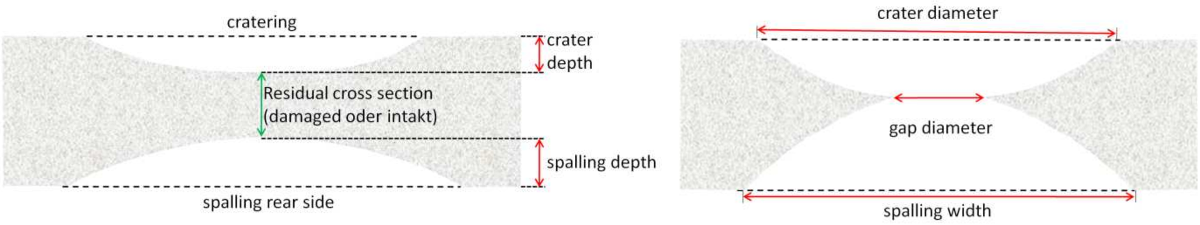

Fig. 8: Potential damaged zones in a reinforced concrete component due to a contact or close-in detonation

Reflections from the rear surface cause scabbing and ejection of debris. At the same time, a crater of fully and partly damaged material is created on the front. If the two regions meet, a breach will result. So, due to local loading, the structural response of reinforced concrete will be critical shearing in combination with cratering on the front side and spalling on the rear side, see Figure 8.

These complex processes are not easily described. Lönnqvist [9] and Gebekken [10] showed that they can reasonably be captured by empirical approaches for reinforced concrete So, the local loading cases on reinforced concrete bridge components were evaluated with the before mentioned validated engineering tools. The diagrams in Figure 9 visualize the calculated residual cross section of a bridge *component A* (left-hand side) and the same results for a bridge *component B* (right-hand side) for different explosive charge weights.

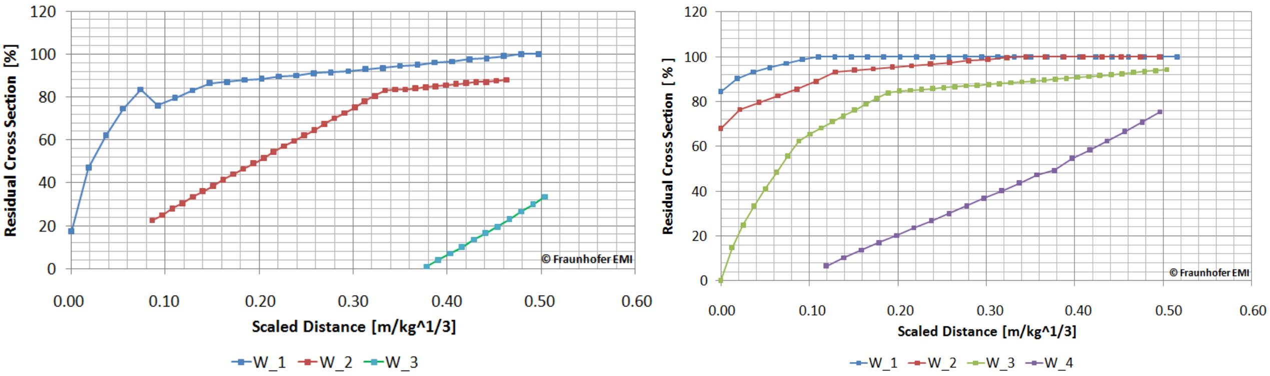

Fig. 9: Residual cross section of the reinforced concrete bridge component A (left) and B (right)

The results of bridge *component A* confirm that only for the smallest explosive charge a complete residual cross section can be accomplished by a scaled distance of 0.5, which also represents the maximum limit for the local failure phenomenology. Larger quantities of explosive charges lead in the regarded scaled distance range to residual cross sections, which are about 90%, or less. A non-totally destructed cross-section is only achieved for the biggest explosive charge for scaled distances greater than 0.38 m/kg$^{1/3}$.

Concerning the bridge *component B*, the explosive masses W1, W2 and W3 lead to a residual cross-section larger than 82 % for a scaled distance of Z = 0.2. For Z = 0.4 and charge weight W4, the residual cross section of the component is still larger than 50 %.

2.2.2 Global Loading Cases on R/C Bridge Components

In this subsection, the global loading due to internal and non-internal explosive scenarios is analyzed after the above exemplified analysis of the local loading cases. To evaluate structure behavior due to global blast loading, simplified Single-Degree-of-Freedom (SDOF) models are “state-of-practice” [11],[12]. In the SDOF-models the external force appears as a product of the structural area A and the blast loading shape p(t). The structural resistance force R(x) reacts against the direction of the external force and tries to bring the structural mass m in the unloaded starting position.

With the additional information of a damage criterion (e.g. critical deflection) and the corresponding force, an iso-damage curve in a so-called pressure-impulse diagram can be derived. This pressure-impulse diagram illustrates the overall structure behavior for an arbitrary choice of peak-overpressure and blast impulse, see [13],[14] for example.

As mentioned before, this approach is also used, to evaluate explosive scenarios in a box-girder of a bridge. The structural properties of the reinforced concrete bridge components as well as the degree of reinforcement are known and, hence, the resistance of these components. In contrast, the values of the internal blast loading for an arbitrary explosive scenario are not known. In the following, a new engineering tool is introduced to calculate the pressure expansion for internal blast and to model a scenario in a box-girder.

The expert tool „TuBlaC“ for calculation of the propagation of a blast wave in a tunnel or closed room was developed at Fraunhofer EMI. Fundamental input parameters for the tool inlucde the dimensions of the room, charge weight and position. The software first calculates the detonation process and the first stage of a free-expanding blast wave. This calculation is carried out in one dimension, i.e., the charge is assumed to be spherical. In the next step, the calculated blast wave is remapped into a three-dimensional finite volume calculation. The third step consists of calculating the propagation path of the blast wave in the tunnel or closed room.

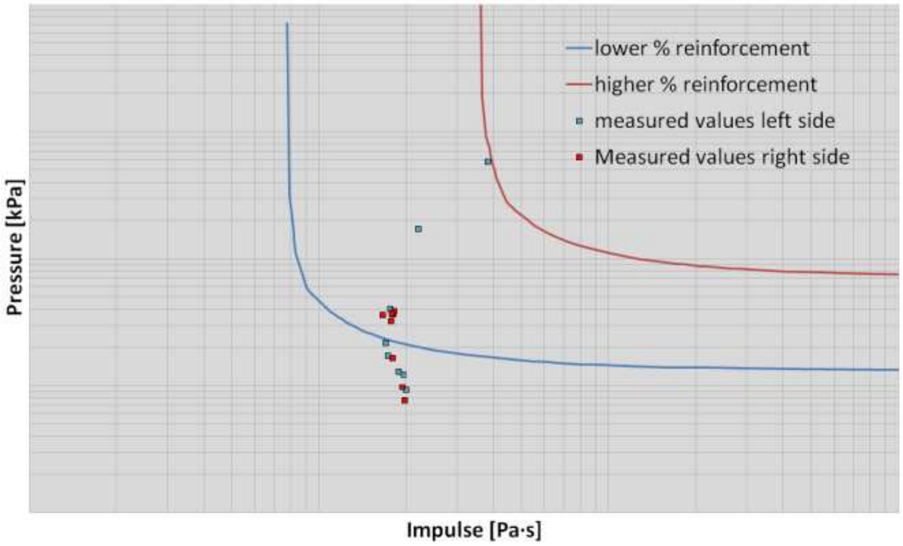

Fig. 10: Iso-damges-curves in conjunction with the numerical calculated pressure and impulses values

The tool „TuBlaC“ offers the user the option to define an arbitrary number of gauge points in the specified room. The tool delivers time histories of the pressure and impulse values for each of these defined points as well as the maximum pressure and impulse values calculated at each wall.

The combination of the developed iso-damage curves resulting from the Single-Degree-of-Freedom model and the results of the calculations with „TuBlaC“ allow a determination of the size of the damaged and intact area in the reinforced concrete box-girder. As a matter of principle with increasing distance to the charge position, the peak-overpressure and blast-impulse are calculated. Figure 10 shows

this approach. High values are closer to the explosion position in the box-girder than lower values. If the calculated „TuBlaC“ pressure-impulse point is below the iso-damage curve, the structure will not fail.
Figure 10 shows furthermore two iso-damage curves with different percentages of reinforcement. Due to global loading, the structural response is bending and hence the percentage of reinforcement is essential for the structural resistance.

The calculations presented in this subsection explored typical detonation scenarios against reinforced concrete components. The results can be used to enhance such elements against typical terroristic threats like improvised explosive devices (IEDs) or vehicle-borne IEDs (VBIEDs).

2.3 Dynamic Response of Integrated Complex Bridge Component Assemblies

In the foregoing paragraph, each construction component was investigated separately regarding its dynamic response to explosive effects. Basing on these results in the following paragraphs, the dynamic resilience of more complex component assemblies representing bigger parts of a bridge construction is investigated. In the investigations, again the numerical simulations are utilized. In addition to the previously mentioned material laws, the RHT-model [3] is chosen to describe the material behavior of the concrete elements in the simulations. The reinforcement of the concrete is modeled by using discrete rebar elements. Figure 10 shows a non-critical result for a chosen detonation scenario for a reinforced concrete box-girder construction and a steel box-girder construction. In the reinforced concrete model, the bridges cables as well as their anchorage are included in the numerical model set-up. With these more complex models, it is possible to calculate a more global effect of a localized detonation scenario in order to give an accurate appraisal of criticality of the regarded damage scenario to the bridge stability.

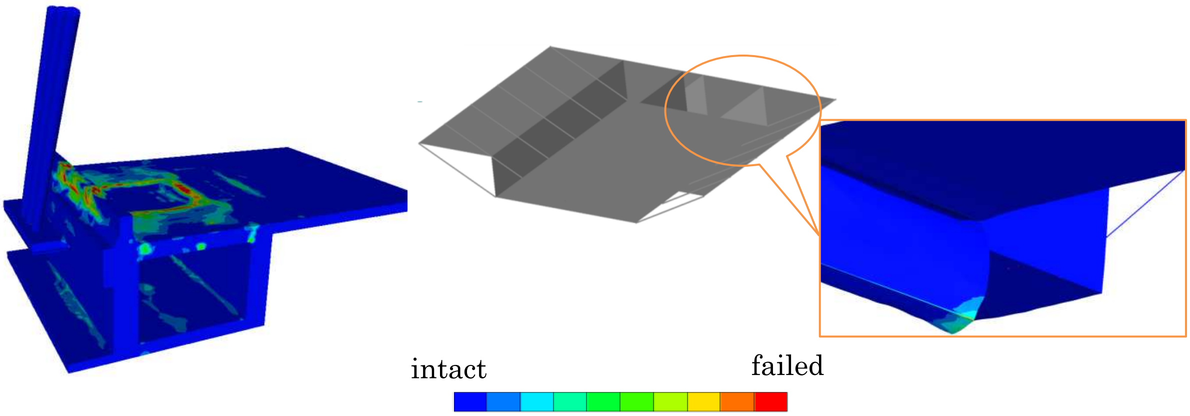

Fig. 10: Results of the numerical simulation for a cable stayed reinforced concrete box-girder bridge construction (left) and for a steel box-girder bridge construction(right)

3. Summary

All the research activities described in this paper investigated the dynamic bearing behavior of single construction elements or groups of these elements. With the knowledge about the local degree of damage, it is thereby possible to evaluate the global bearing behavior of the bridge by the use of other not further specified numerical methods. An example for such a global stability analysis is presented in [15].

Based on the described research, the critical explosive mass for bridge cables can be defined with respect to the cable diameter, the prestress and the location of explosive application. In addition, a numerical model for the cables has been developed and presented, which allows, on the one hand, a good reproduction of the model tests and, on the other hand, a validated damage prediction in full-scale. Fast predictions with engineering tools helped to classify critical reinforced concrete bridge components. The vulnerability has been assessed as limit values depending on the scaled distance. More complex structures have also been analyzed in finite-element simulations. This numerical approach enables a superposition of the static and high dynamic loads. Thereby, the total stress resultants can be calculated and evaluated.

In summary, the methods and results presented in this paper allow a classification of the criticality of damage to different bridges and their specific components. This work builds the basis for enhanced measures countering terroristic threats.

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