# Dynamic Response of Bridge Components under Explosive Effects

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**Abstract –** Buildings of critical transport infrastructure, such as tunnels and bridges, often reside on special load-bearing members and conditions. The vulnerability concerning terroristic threats and the criticality for such buildings are the focus of the described study.

In order to evaluate the criticality of different possible detonation scenarios, several components of infrastructural buildings are analyzed using different state-of-the-art methods. Reinforced concrete components under contact and close-in detonation loading are examined using validated engineering tools. The presented evaluation processes enable thereby the definition 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 confirmed appraisal for internal detonation scenarios too.

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 constructions and components are not comparable to office buildings of critical infrastructure (embassies, administrations and ministries, tower buildings) such as reinforced concrete walls, columns and masonry. Therefore, they require new analysis and classification approaches, which are addressed and summarized in the proposed paper.

## 1. Introduction

Roads make up a crucial part of the German 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. So, tunnels and bridges are an essential part of road traffic. The 2006 attempted attack against the Hohenzollern Bridge in Cologne has shown that terrorist acts also have to be considered in Germany.

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

An important part of the risk analysis consists of examining the degree of damage caused to structural components of, in this case here, 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 buildings, the user and the surroundings are considered, and counter-measures are being developed. The vulnerability to terrorist threats and the criticality of bridge structures are the focus of the described study.

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.

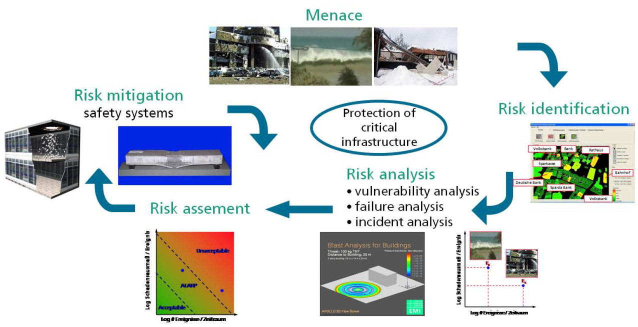


FIG. 1: Process scheme for the protection of critical infrastructure

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.

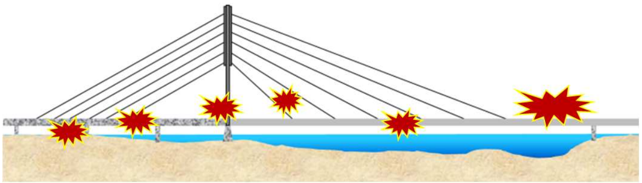

FIG. 2: Typical construction of a cable-stayed bridge in conjunction with possible detonation locations

## 2. Terror Event Database (TED)

To assess the possible threat of terrorist attacks against critical infrastructure, it is necessary to analyze the history of terror 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 at the Fraunhofer Ernst-Mach-Institute (EMI) a MS Access database was set up. Publicly available data was used as basis for the in-house Terror Event Database (TED).

The sources for the database were collected from different media. Main sources when collecting the data were books [1-5], publicly available online newspapers [6-17] and the data that was available at the Terrorism Knowledge Base of the Memorial Institute for the Prevention of Terrorism [18]. The terroristic events were stored in the database with the following information: date of the event, number of injuries and fatalities, country, where the incident took place, terrorist group, target object and the used tactic.

The target objects are grouped into three main categories (governmental, civil and industrial) and further in sub-categories (e. g., military, media, tourism, education etc.). Presently the database includes approximately 35,000 incidents from 1968 to 2007. 179 countries and 1042 known terrorist groups are stored. 101 tactics (e. g., car bomb) were captured and also 469 target objects which are grouped in the above-named categories. The database will be continuously enlarged and completed. Hence, this database offers a good basis for risk analysis.

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 3 shows the tactics how terrorist events against bridges and tunnel were arranged. 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.

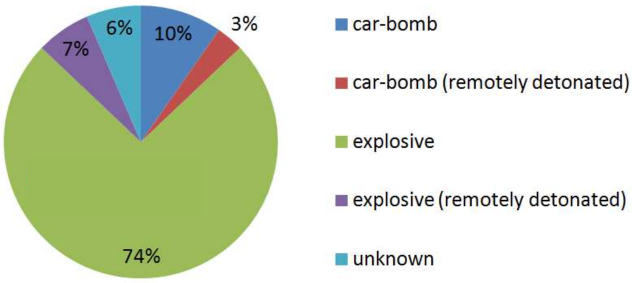


FIG. 3: Tactics against bridges and tunnels worldwide

A further result of the database evaluation was to determine the place on the building where the attacks can occur. Figure 2 shows the places of the bridge prone to terrorist activities with explosive devices. For this reason, the investigation will focus on these locations.

With the aim of the TED event analysis, different standard scenarios were appointed. One result was the definition of different charge weights and the second result were the places of the bridge where these defined charge weights could occur.

A next step is to characterize the structure behavior due to these scenarios. The estimation of every bridge component gives an answer to the criticality of each scenario.

## 3. Dynamic Response of Bridge Components

Figure 2 shows a typical construction of a cable-stayed bridge. Besides the bridge cables, the structure consists of reinforced concrete parts and several steel parts. The dynamic bearing behavior of these three kind of bridge components is analyzed percisely in the following sections.

### 3.1 Reinforced Concrete Components

Reinforced concrete components play a significant role in the bridge's global load-bearing capacity. As dynamic analysis of reinforced concrete is a standard field for the assessment of building security, the load-bearing behavior and capacity are already well understood [19, 20]. Consequently, simplified engineering approaches such as Single-Degree-of-Freedom models or empirical engineering formula can be used and are described in this section [21-23].

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

Building components in general show different response patterns depending on the blast-loading intensity. Depending on charge weight W and distance R, there are local and global deformation modes such as critical bending or shearing of the structural component, which can occur. The scaled distance Z allows a differentiation between local and global loading, see equation 1. Small values result in shear loading, large scaled distances lead to a bending response [23].

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 design, three categories of the carriageway slabs and four different types of the columns have been investigated.

For each structural component, the critical value for the scaled distance was determined. Meaning, 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 small significant influence on the structural resistance [24, 25]. But in the case of global loading, the structure reacts with 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.

### 3.1.1 Local Loading Cases on R/C Bridge Components

Contact detonations or detonations at very small scaled distances result in a deformation phenomenology, which is very complex. An extremely sharp shock front with pressures in the range of 10 GPa or more is transmitted from the explosive into the structure.

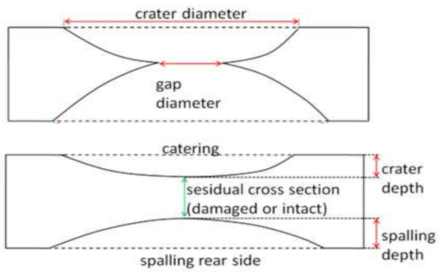


FIG. 4: Potential damaged zones in a reinforced concrete component due to a contact or close-in detonation

Reflections from the rear surface cause scabbing and ejecta. At the same time, a crater of fully and partly damaged material is created on the front. If both regions coalesce, total perforation will occur. 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 4.

These complex processes are not easily to describe. Lönnqvist [31] and Gebekken [32] showed that they can reasonably be captured by empirical approaches for reinforced concrete The local loading cases on reinforced concrete bridge components were evaluated with the before mentioned validated engineering tools. Figure 5 shows the residual cross section of a bridge component A and Figure 6 the same results for a bridge component B for different explosive charge weights.

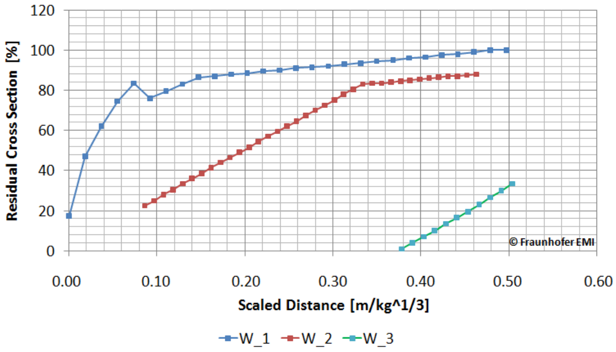


FIG. 5: Residual cross section of the reinforced concrete bridge component A

The results of component A clarify 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 less than 90%. A non-totally destructed cross section is only archived for the biggest explosive charge for scaled distances greater than 0.38 $m/kg^{1/3}$

Concerning the bridge component B, the explosive masses $W_1$, $W_2$ and $W_3$ lead to a residual cross section larger than 82 % for a scaled distance of $Z = 0.2$. For $Z = 0.4$ and charge weight $W_4$, the residual cross section of the component is larger than 50 %.

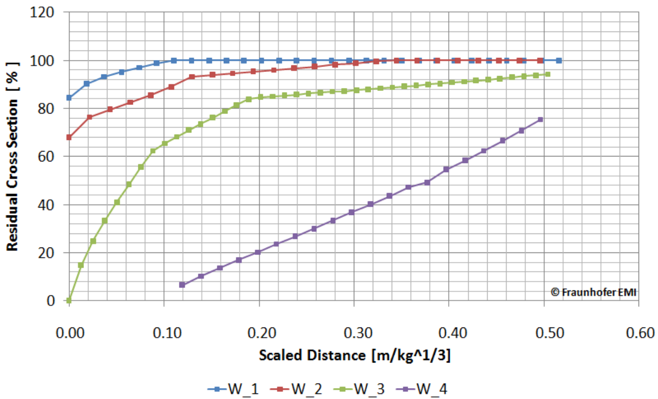


FIG. 6: Residual cross section of the reinforced concrete bridge component B

### 3.1.2 Global Loading Cases on Bridge Components

After the analysis of the local loading cases, global loading due to internal and non-internal explosive scenarios is analyzed in the following subparagraph. To evaluate structure behavior due to global blast loading, simplified Single-Degree-of-Freedom models are "state-of-practice" [27, 28]. Figure 7 illustrates the principles of the SDOF model. 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 derivated. This pressure-impulse diagram illustrates the overall structure behavior for an arbitrary choice of peak-overpressure and blast impuls; see [29-30] for example.

This approach is also used, as mentioned before, to evaluate explosive scenarios in a box-girder of a bridge. The structural properties of the reinforced concrete bridge components and the degree of reinforcement are known and, hence, the resistance of these components. Unknown are the values of the internal blast loading for an arbitrary explosive scenario. In the following, a new engineering tool is introduced to calculate the pressure expansion for internal blast and hence a scenario in a box-girder.

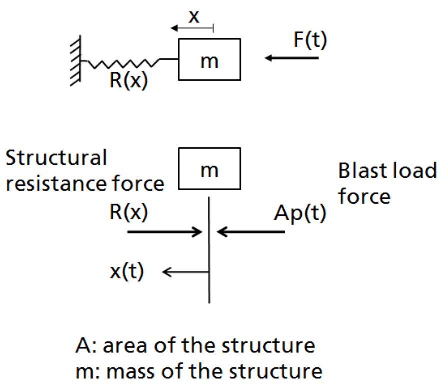


FIG. 7: Fundamentals Single-Degree-of-Freedom function

At Fraunhofer EMI, the expert tool „TuBlaC" for calculation of the propagation of a blast wave in a tunnel or closed room was developed. Dimensions of the room as well as charge weight and position are the fundamental input parameters for the tool. In a first step, the software calculates the detonation process and the first stage of a free expanding blast wave. This calculation occurs in one space dimension, i.e., the charge is assumed to be spherical. In a next step, the calculated blast wave will be remapped into a three-dimensional finite volume calculation. Subsequently, the calculation of the propagation of the blast wave in the tunnel or closed room occurs.

The user of „TuBlaC" has the option to define an arbitrary number of gauge points in the room. The tool delivers time histories of the pressure and impulse values at these defined points as well as the maximum pressure and impulse values occurring 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. With increasing distance to the charge position, the peak-overpressure and blast-impulse are calculated. Figure 8 shows this approach. High values are closer to the explosion position in the box-girder. If the calculated „TuBlaC" point is below the iso-damage curve, the structure will not fail.

Furthermore, Figure 8 shows 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 in this subparagraph explored typical 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).

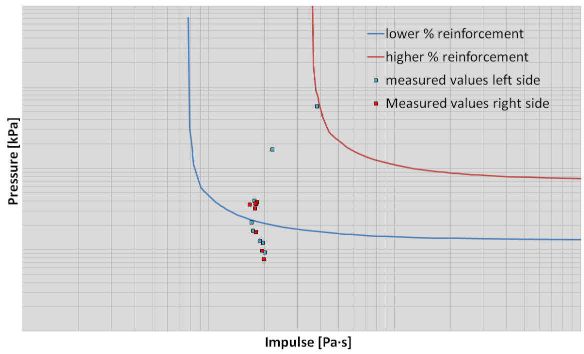


FIG. 8: Iso-damages-curves in conjunction with the numerical calculated pressure and impulse values

## 3.2 Local and Global Loading Cases on Steel Components

After the reinforced concrete components in the following paragraphs, the steel components of a bridge construction will be the focus of the described investigations. For the 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. For the lack of these tools, the dynamic bearing behavior of the regarded component is analyzed using the well-established combination of scaled model tests and accompanied numerical simulations. After the validation of the simulations of the model test against the results of these tests, the numerical model can be transferred to full-scale dimensions. In these 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.

In the first subparagraph, the dynamic behavior of normal-strength steel plate type construction elements is outlined.

Focus of this paper section is the research of the dynamic bearing behavior of the high-strength steel bridge cables.

### 3.2.1 Fundamentals of the Numerical Simulations

All numerical simulations mentioned before and in the following were done using a program code basing on the finite method using finite-volume differences. The used code AUTODYN belongs to the class of the so-called hydrocodes.

Characteristic of this class of numerical codes is the explicit time integration scheme in conjunction with the solution process, which solves the equitation of the conversations of mass, momentum and energy simultaneously. Another fundamental characteristic of the hydrocodes is the distinction in hydrostatic and deviatoric stress components in the material law description. The code enables the interaction of Lagrangian mesh domains for structural dynamic calculations with Eulerian fluid mesh domains. This combination offers the possibility of a fully coupled calculation of a detonation scenario and the linked blast wave propagation in conjunction with the structural response of the construction to the blast loading.

The medium air is described in all simulations using the ideal gas equation of state. In this thermo-dynamic equitation the pressure of the gas is correlated to the gas density and the internal energy, which is also related to the gas temperature (see Eqn. 2 and 3)

$$p = (\gamma - 1)\rho e \qquad (2)$$

$$e = c_v \, T \qquad (3)$$

The numerical material model of the explosive is governed by the Jones-Wilkinson-Lee equation of state. This equation enables the numerical calculation of the detonation process in the explosive and is transferred into the before mentioned ideal gas equation of state after the phase transition and expansion of the explosive.

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \qquad (4)$$

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.

$$Y(\varepsilon_p, \dot{\varepsilon}_p, T) = [A + B\,\varepsilon_p^n][1 + C \log \dot{\varepsilon}_p^*][1 - T_H^m] \qquad (5)$$

### 3.2.2 Steel Plates

Figure 9 shows the created model test set-up, which is created in a scale M of 1:10. The test specimen is pinned four-sidedly in a rigid steel bracket. The clamp of the plate is conceived, so that a pull out of the steel plate during the loading phase is avoided. The also scaled explosive charges are placed in the intended distance to the plate surface using a styrofoam spacer. Figure 10 visualizes the results of the test for a defined scenario.

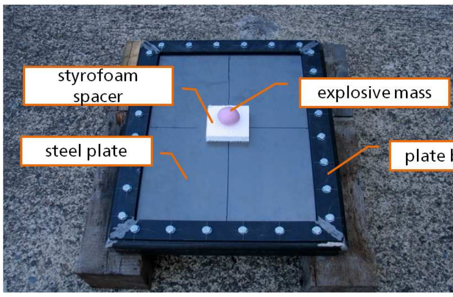


FIG. 9: Model test set up for the steel plates

This model test set-up is simulated in the hydrocode mentioned above. The results of the simulations are presented in Figure 10, too. As well for the front side as for the backside of the plate, the size of the disrupted area is calculated very sufficiently in the numerical code. Besides, the deformation Figure of the plates is also computed in good agreement to the experiment. So, the numerical description of the dynamic steel behavior can be regarded as validated.

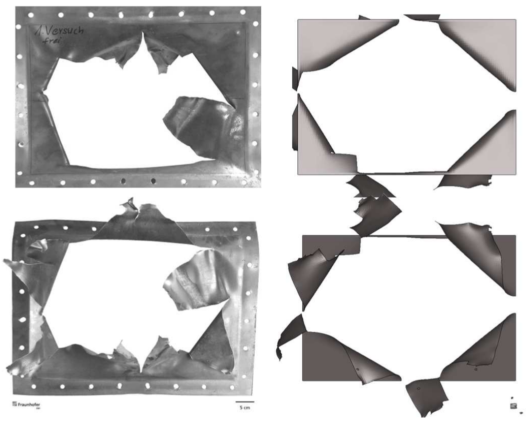

FIG. 10: Results of the experiments (left) and the numerical simulation right for the front (top) and backside (bottom)

In Figure 11, an application of the consecutive full-scale numerical model is presented.

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.

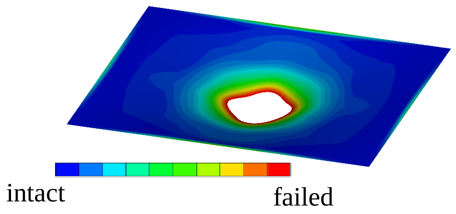


FIG. 11: Numerical prediction of the damage on a full scale steel plate for a given scenario

### 3.2.3 Steel Cables

In the model scale tests (M1:10 to 1:50), a cold-drawn high-strength steel strand cable is loaded by a contact detonation. The Hopkinson-Cranz scaling law [33] is obeyed for both cable and explosive charge to allow upscaling of the results to real bridge dimensions. The damage resulting from the detonation of the explosive is quantified by both counting the destructed wires of each strand and by determining the static residual strength in tension. 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 commonly used pre-stress of 30 % of the tensile strength, in turn, leads to a damage increase of about 30 %.

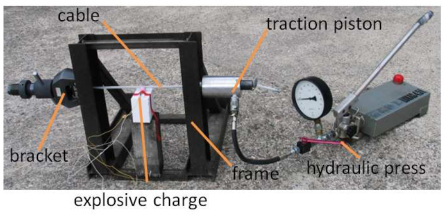


FIG. 12: Experimental test set up for the bridge cables

Furthermore, a significant sensitivity on the geometrical placing of the explosive could be identified in the model tests. This dependency generates a deviation damage variation of about 25 to 30 % for the tested explosive quantities. The diagram in Figure 13 summarizes the results of the conducted model test series. Each loading scenario is tested several times in order to evaluate the reproducibility of the results. The derivation of the results is therefore also visualized in the diagram.

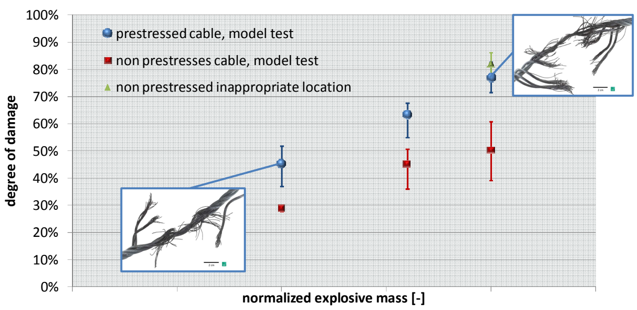


FIG. 13: Measured degree of damage in terms of lost cross section depending on explosive mass, prestress and location

To fill remaining gaps of the experimental research, also numerical studies are carried out. The expected damage on model-scale and full-scale bridge cables with different diameters and explosive masses can be calculated using finite-element simulations Therefore, the main characteristics of a steel strand cable have to be modeled. These are, besides the grade of steel, the stranding and fill factor of the cable. Another main mechanical characteristic of a cable is the very limited compression stiffness.

Because of the reason that cables in general are very slender constructions, whit a high variety of design variations, the pre-assigned qualities are modeled by a mesomechanical approach presented in Figure 14.

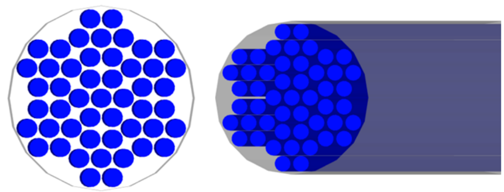

FIG. 14: Mesomechanical numerical model for bridge cables

In the numerical model, several wires are simplified to one steel bar. The stranding of the rope is captured by a frictional contact between them and a circumferential coating shell tube.

The fill factor and the steel grade correspond exactly to the modeled type of cable. The depicted model configuration represents a compromise between numerical simplifications and correct reproduction of the rope phenomenology. Also for this reason, the quality of the numerical results is validated against the experimental data and the influence of the chosen simplifications is analyzed by the use of a parametric study, which are both discussed in the following.

In the numerical model each element row in cable lengthwise direction represents one wire of the model 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 model build-up and resolution, the degree of damage can be compared to the experimental results. Besides the number of the destructed wires, with this methodology also wires can be identified, which are already plasticized due the loading. So, the residual tension strength can be derivated from the non-plasticized cables areas and can thereby also be compared with the experimental results.

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

In order to gather the effect of the friction coefficient, the same loading scenario was calculated with a friction coefficient µ of 0 compared to another simulation with a coefficient µ of 0.6. The observed derivation 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.

The other simplification in the numerical model is the use of a coating in order to simulate the confinement of the strands resulting from the stranding. The thickness of this coating is set equal to the diameter of one cable wire, which enlaces the cables notionally.

That this is a valid approach underlines the parametric study presented in Figure 15.

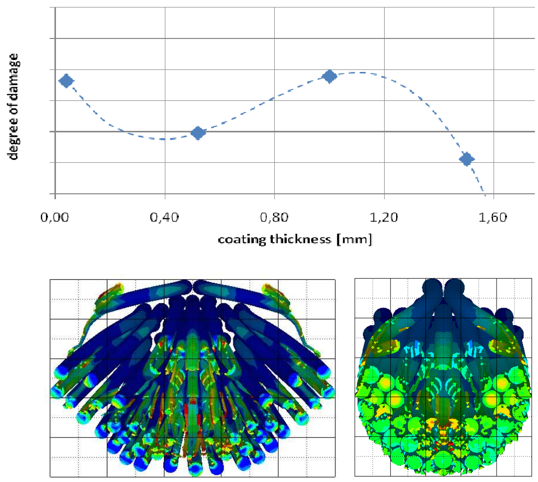


FIG. 15: Results of the parameter variation of the coating thickness (top); deformation figure for a thin coat (bottom left) and a thick coat (bottom right)

With no or a very thin coating, the barrels spread out widely due to the loading. With a thicker coating, the barrels are confined in that way that the deformation and the damage Figure is very comparable to the experimental results. The diagram shows that further increase of the coating thickness decreases the calculated degree of damage which is not realistic and also on the unsafe side of the design approach.

Another point that was investigated in the numerical preliminary calculations was the way of modeling the pretension in the prestressed cables. One way of modeling this pretension is to simulate the direct and correct prestressing process.

The simulation of this process is numerical, combined with great computational costs. Another way 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 region of the cable is reduced perpetuating the stiffness of the cable. The difference between the prestressed and non prestressed material description is visualized in the diagram in Figure 16.

Comparing the results of the direct method with the indirect method, similar results are calculated in the numerical models.

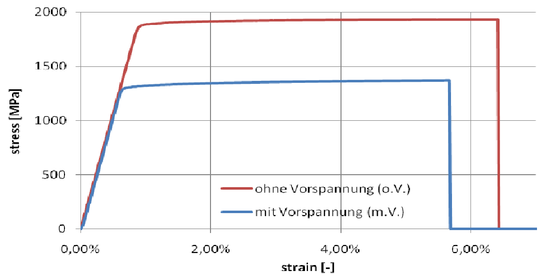


FIG. 16: Stress-strain correlation for a prestressed (blue) and non prestressed (red) steel

Because of the reason that the indirect method is computationally much more efficient, this method was used 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 17 points out a very reasonable reproduction of the lost 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. Also, the dependency on the geometrical location of the explosive mass is replicated in good agreement with the experimental observations.

An advantage of the model and its simplifications is the fact that it can be easily transferred to full scale without any further assumptions. After the successful validation of the numerical model against the experimental results, the model is transferred to the full scale in order to calculate and evaluate the effects of different possible detonation scenarios. The diagram in Figure 18 shows the corresponding results.

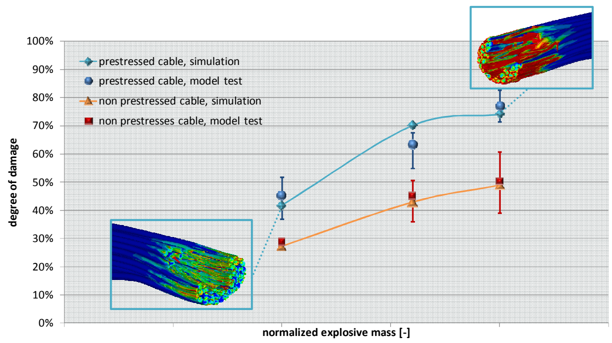


FIG. 17: Comparison of experimental an numerical results

Analyzing the results of the model tests and the full-scale simulations, the degree of damage can be described for both scales by a mathematical approach with 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.

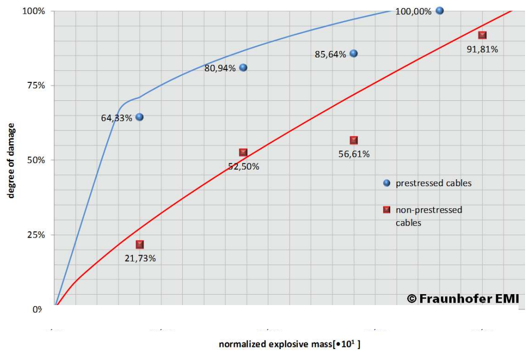


FIG. 18: Numerical damage prediction for a full scale cable (points) and derivated analytical failure lines

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.

#### 3.2.4 Integrated Complex Bridge Component Assemblies

Based on the results of the foregoing paragraphs, the dynamic resilience of more complex component assemblies representing bigger parts of a bridge construction is investigated in the following. In the investigations, again the numerical simulations are utilized. In addition to the before mentioned material laws, the RHT-model [20] 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 19 shows the non-critical results for a chosen detonation scenario for a steel box-girder and for a reinforced concrete box-girder construction. In the reinforced concrete model, also the bridges cables and their anchorage are included in the numerical model set-up.

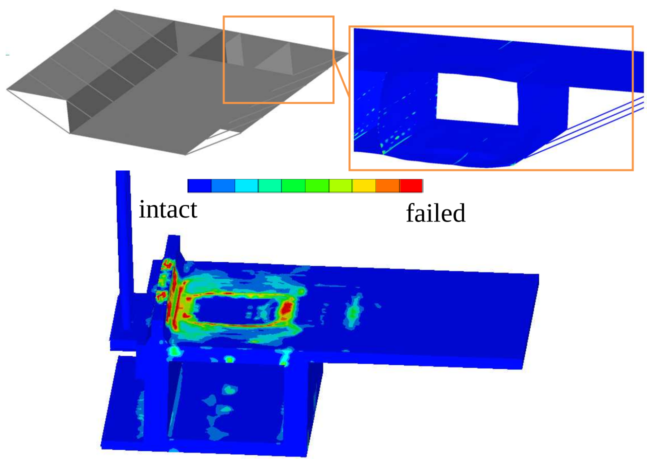


FIG. 18: Numerical model and results for a Steel box-girder bridge construction (top) and results for a cable stayed reinforced concrete box-girder construction (bottom)

With these more complex models, it is now possible to calculate a more global effect of a localized detonation scenario in order to give an appraisal of criticality of the regarded scenario to the bridge stability.

## 4. Summary

All the research activities described in the foregoing sections investigated the dynamic bearing behavior of single construction elements or groups of these elements. By knowing the local degree of damage, it is then possible to evaluate the global bearing behavior of the bridge by the use of other not further specified numerical methods [34]. An example for such a global stability analysis finally shows Figure 19. The picture visualizes a possible deformation Figure which can occur if a cable or a group of cables fail.

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, 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 different bridges and their specific components. This work builds the basis for enhanced measures countering terroristic threats.

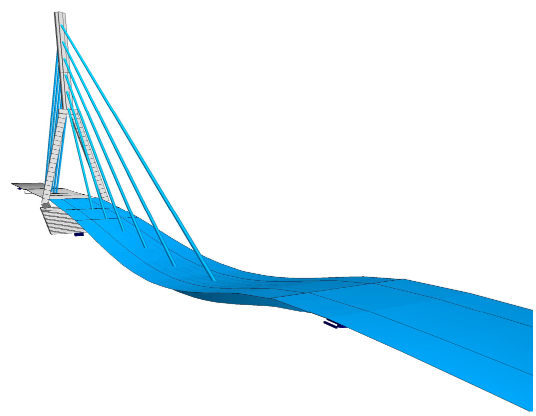

FIG. 19: Exaggerated deformation Figure of a cable stayed bridge after failure of a cable group © Schüssler Plan Ingenieurgesellschaft mbH 2009

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