Bridge design – Relevance and efficiency of protective measures for bridge structures under severe loading

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ABSTRACT: The submitted paper presents an investigation methodology for measures to protect representative types of bridge structures from severe local and global loading conditions. It is based on a systematic evaluation of relevant scenarios such as prognosticated wind loads and floods caused by increasing global temperatures as well as accidental and intentional loss of structural members caused by impact, fire or explosions. In a first step these scenarios are calculated in a finite element bridge model to be subsequently compared with a standard bridge design. Dynamic impact scenarios such as the sudden member loss are numerically simulated in a dynamic time step integration. The degree of deterioration is finally classified along national and European guideline classification. Subsequently the effectiveness of measures is evaluated in the same model to provide a comparison to the reference state. The structural evaluation is attended by a comprehensive evaluation including the impact on the traffic situation to determine a generic classification of vulnerability and criticality. The investigations have been conducted within the comprehensive research activity called "SKRIBT – Protection of critical bridges and tunnels in the course of roads" coordinated by the German federal highway institute.

1 RESEARCH ACTIVITY CONCEPT

The investigation of bridge resilience subjected to hazardous incidents such as natural hazards, terrorist attacks and large scale accidents is conducted in the framework of a research study (SKRIBT – Protection of critical bridges and tunnels in the course of roads) coordinated by the German federal highway institute (BAST) with contributions from a consortium of universities, research institutes, end-users and related experts such as Schuessler-Plan engineering consultants. The three-year project is based on a comprehensive approach (see figure 1) for bridges as structures and parts of an overall traffic system. The presented paper however is focused on the resilience of bridge structures as a part of this general analysis and the relevance and efficiency of protective measures under severe loading conditions. The main objective is the development of a methodology for evaluation of bridges and appropriate measures to enhance the structural safety and security. To prepare the reasonable allocation of measures a vulnerability study of a representative variety of bridge structures is conducted comparing actions caused by threats to the bridge resistance. Being technically proven the effectiveness of measures is evaluated and recommendations for future bridge structures are derived.

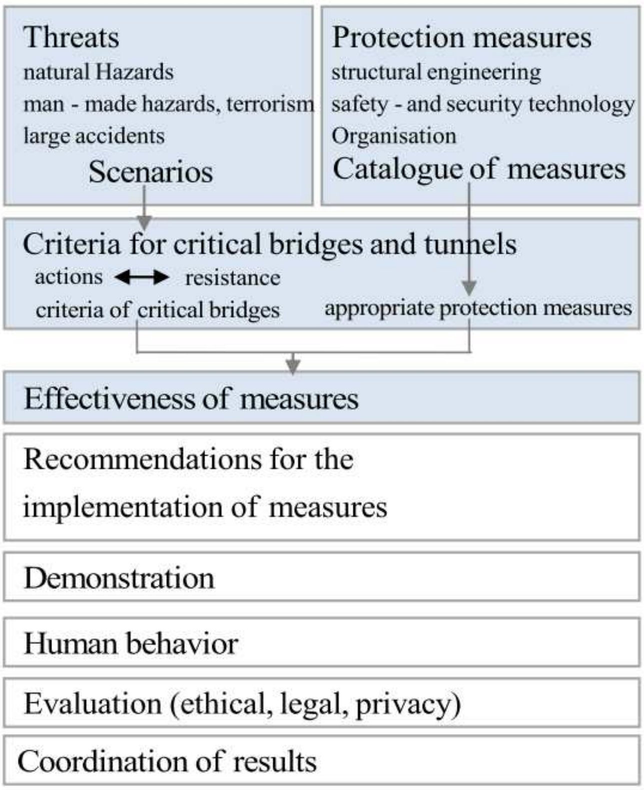

Figure 1. Structure of the research project with regard to bridges

In the presented paper the methodology is shown using an example of a generic stay cable river bridge.

2 CATALOGUE OF MEASURES

The security of a bridge structure is generally influenced by the choice of material, the design concept, the intensity of the individual scenario and the implementation of specific technical equipment and installations. The development of additional protective measures for a bridge structure is dominated by the following principles:

- Prevention of progressive collapse of the global structure induced by local failure. Development and application of new design concepts including alternate load paths and/or segmentation principles.
- Ultimate limit state design approach for extreme and exceptional scenarios like storms, floods, earthquake and impact (probabilistic approach) as well as scenarios with a low event risk but a high risk of collapse such as explosions.
- Implementation of innovative materials, such as micro-reinforced High Performance Concrete (HPC), fire resistant concrete and energy absorbing concrete.

Two major categories of objectives can be classified to enhance the resilience of a single or multiple structural members [2, 3]:

Category 1: Increase local resistance – internal and external protection (Direct Protection DP)

These measures aim at increasing the local resistance of a single structural component to better withstand a specific scenario. Alternatively measures of this category provide external protection to increase the local resistance. Table 1 shows a list of relevant protective measures and the effect of the protection on the structure and the user. Different measures are addressed to different single or multiple scenarios or even combination of events.

- Strengthening of important structural members against impact or explosions by highly ductile and/or energy absorbing materials.
- Strengthening of important structural members by design, new ultimate limit state design criteria is to be defined → see chapter 4 and 5.
- Restriction of accessibility to the most vulnerable components by barriers, direct access control as well as fortification.
- Fire protection measures for fire exposed structural components. Material immanent or external protection.
- Adjustment of freeboard to predicted flood incidents due to climate changes.
- Mitigation of large scale accidents caused by deck icing by using an innovative geothermal heating technology instead of conventional de-icing methods.

Category 2: Compensation of local failure (Indirect Protection IP)

The increase of the local resistance (DP) might be limited due to functional, ethical or aesthetical reasons. However a local damage or failure of a structural component does not necessarily lead to a loss of integrity of the global structure or a complete progression of damage. The following design criteria are suitable to keep the local failure localised.

- The “design criteria” requires alternate load paths to compensate the failure of a single structural member. Consequently the criteria implicate redundancy elements which provide a redistribution of loads to compensate the effect of local failure. Statically undetermined systems can be classified as indirect protective measures.
- Alternatively a local failure might be localized by a segmentation of the structure which is able to isolate the effect in a local section of the bridge structure.
- Securing global redundancy by a separation of the superstructure/global structure for each traffic direction.

Table 1 Additional measures to enhance bridge resilience

Description	Scenario	Category	
		Structure	User
Micro Reinforced HPC	E, I	DP	IP
Energy Absorbing Concrete	E, I	DP	IP
Barriers	E, I	DP	IP
Fortification	E, I	DP	IP
Wind deflector	W	-	DP
Design criteria	E,I,W,S,F	DP	IP
Fire protection	Fi	DP	IP
Freeboard	F	DP	IP
Alternate load paths	E, I, Fi	IP	IP
Segmentation	E, I, S, Fi	IP	IP
Separation of structure	E,I,Fi	-	IP
Geothermal heating	I	IP	DP
Surveillance	E, I	IP	IP
Early warning system	E, I, Fi	-	DP
Traffic guidance system	E,I,W,F	-	DP
Illumination	E	-	DP
Sensor detection	E,CB,W	-	DP
Rescue lanes	All hazards		IP
Communication x2Car	All hazards		DP

Legend of Abbreviations: E – Explosion, I – Impact (car, ship), S – Seismic, W – Wind, F – Floods, Fi – Fire, CB Chemical biological, DP – Direct Protection, IP – Indirect Protection

Apart from the direct or indirect protection of the bridge structure the implementation of technical equipment and installations are suitable to improve the bridge resilience especially with respect to the user and the first responders. In contrast to tunnels, bridges are in present rarely fitted with such technical equipment. Useful measures are illustrated in table 1.

3 SZENARIO DEFINITION AND ANALYSIS

A large variety of threats is considered and investigated under the aspects of their possible impact on the structure, the user and the organisations such as first responders. With respect to the bridge structure the most severe incidents are potentially caused by natural and man-made hazards. Each threat has to be investigated and classified qualitatively and quantitatively to generate a representative scenario for calculation and evaluation purpose.

Natural hazards are standardized based on statistical data which has been collected over the past decades. Prognosis for future developments caused by climate changes are indicated by research investigations of insurance companies [23] and weather forecast institutes [24]. The resulting increase of loads caused by natural hazards is implemented in the semi-probabilistic approach which ensures the applicability of the state-of-the-art design strategies in Eurocode 1 (see chapter 4). Thus the probabilistic character of the investigation strategy is ensured.

Man-made hazards can hardly be classified by statistical data especially with respect to terrorism. Existing database such as the Terror Event Database (TED) collected and updated by the Fraunhofer EMI [22] contain a diversity of events which lead to a statistical validation for selected incidents. However many scenarios have individual attributes impossible to be generalized and classified in a basic population. Furthermore the resulting probability for a terroristic incident is lower by order of magnitude in comparison to natural hazards so that a different approach has to be found.

For exceptional loading cases Eurocode 1991-1-7 [5, 13] provides with a half-deterministic approach which enables the user to define a major loading situation by choice. Thus an apparently relevant event can be determined and defined as a nominal value for the major load situation being statistically combined with secondary loads. The resistance of the structure is evaluated in the conventional semi-probabilistic approach in conformity with the general Eurocode definitions. Details of the application are demonstrated in chapter 4 and 5.

The scenarios considered in the research project are documented in table 2.

Table 2 Relevant Scenarios and possible approach

Description	Method	
	Probabilistic	Deterministic
Explosion by intensity		
Man-carried bomb		X
Car bomb		X
Truck bomb		X
Fire by intensity		
Car Fire		X
Truck Fire		X
Large-scale Fire		X
Mechanical impact		X
Natural Hazards		
Floods/Underwashing	X	
Heat	X	
Wind	X	
Seismic incidents	X	

4 CLASSIFICATION IN EUROCODE SAFETY CONCEPT

The European standards are based on a probabilistic method for the combination of natural hazards with standard dead loads and life loads [4, 21]. The safety level is controlled by the choice of safety factors for the calculations of structural integrity (ULS – Ultimate limit state) and serviceability (SLS – Serviceability limit state). A reliability index β prescribes the effective safety margin (combination of event risk and failure probability) dependant on the frequency of an event and the resistance of the structure under an individual loading combination [18].

Table 3 Operative failure probability p_f and according reliability index β dependant on the frequency of an event

p_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
β (1 year)	1.28	2.32	3.09	3.72	4.27	4.75
β (50 years)	-	0.21	1.67	2.55	3.21	3.83

Based on the reliability index β a generalization of the probabilistic approach leads to a simplified and broadly applicable semi-probabilistic model. The resulting safety factors γ and ψ (see equations 1-3) include the reliability index β implicitly for different load situations and frequencies.

Permanent and temporary load combination

$$\sum \gamma_{Gj} \cdot G_{kj} \oplus \gamma_P \cdot P_k \oplus \gamma_{Q1} \cdot Q_{k1} \oplus \sum \gamma_{Qi} \cdot \psi_{0i} \cdot Q_{ki} \tag{1}$$

Extraordinary load combination

$$\sum \gamma_{GAj} \cdot G_{kj} \oplus \gamma_{PA} \cdot P_k \oplus A_D \oplus \psi_{11} \cdot Q_{k1} \oplus \sum \psi_{2i} \cdot Q_{ki} \tag{2}$$

Seismic load combination

$$\sum G_{kj} \oplus P_k \oplus \gamma_1 A_{ED} \oplus \sum \psi_{2i} \cdot Q_{ki} \,, \tag{3}$$

with G – permanent (dead) loads, Q – live loads, A - extraordinary loads, P – Loads induced by Prestressing, i,j – control variables, ⊕ - "combined with"

The load situations for the investigated scenarios are characterized by an extremely low repetition frequency and are therefore assigned to the extraordinary or the seismic load combination. Man-made hazards are analyzed by a determined dominant scenario A_D in the sense of the probabilistic methodology as event risk values can hardly be defined. In fact the event risk is statistically set equal to one and the extraordinary load combination is chosen for the combination with other load cases.

5 CRITICAL SCENARIO ANALYSIS

The criticality of a scenario for a structure is determined by an individual analysis comparing actions and resistance of the structure. This method is shown exemplary for a generic stay cable bridge.

Scenario selection, spatial and time discretisation

The abrupt loss of a cable group can potentially cause failure of further structural elements. The sudden failure of structural elements might lead to the collapse of large structural sections or the entire structure. A significant mass inertia effect of this bridge section evokes supplementary loads in the comparatively short time frame of oscillation (see figure 2).

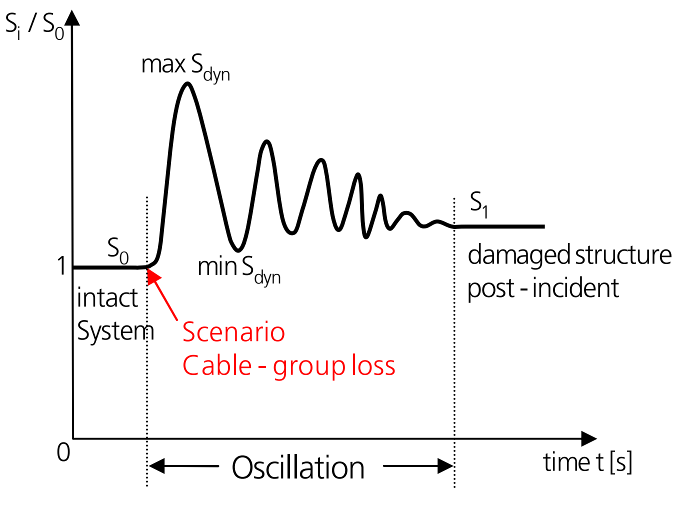

Figure 2. Maxima and minima of internal forces caused by a sudden loss of a structural member

With the help of a structural dynamical analysis of this dynamical incident including the initial (statical) internal forces and deformations the maxima and minima of internal forces can be determined. In contrast to a possible simplified method using (factorized) equivalent statical loads for the mass inertia effect the structural dynamical calculation leads to improved (more realistic) results [3, 14]. The abrupt loss of a cable is a short-time and momentary incident which can adequately be investigated using a time step integration method to solve the equation of motion. The dynamic response of the structure is determined for all cable loss scenarios respectively. The analyses and evaluation of the structure is obtained by comparing the dynamic response (incident) with the static response of the structure referring to the state of pre-incident.

A common simplification method for cables in statical calculations is the discretisation by beam elements with an additional internal pre-stressing. This method delivers appropriate results as long as the dominant loads do not cause significant changes in stress-state. For structural dynamical problems with varying stress-states during the bridge sway the nonlinear stress-strain behavior of the cables has to be taken into account to achieve appropriate internal forces [6, 7, and 10].

Results

Figure 3 illustrates the generic bridge structure with six cable groups carrying a 350 m (1150ft) free span between the inverse Y-shaped Pylon and the neighboring riverside column.

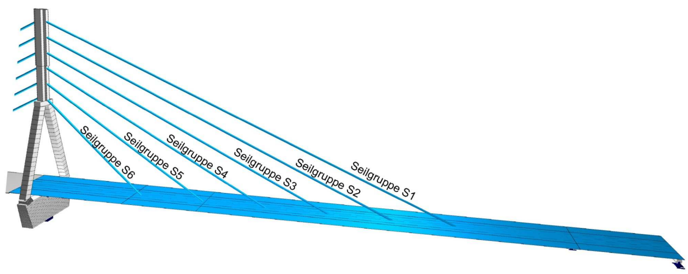

Figure 3. Analyzed (exemplary) stay-cable bridge structure in global Finite-Element model with six stay cable groups

The cable group loss is investigated for each cable group as the initial scenario to determine the most severe effect on neighboring (intact) cable groups, superstructure and Pylon respectively. For the neighboring cable groups and the superstructure it was found that the loss of group three leads to the highest increase of internal forces. The extraordinary load combination (Eq. 2) with reduced safety factors is used to compare the internal forces with the regular pre-incident design forces (Eq. 1) enlarged by safety factors for permanent and momentary loads.

Figure 4 shows that such comparison does not lead to an exceedance for the neighboring cable groups.

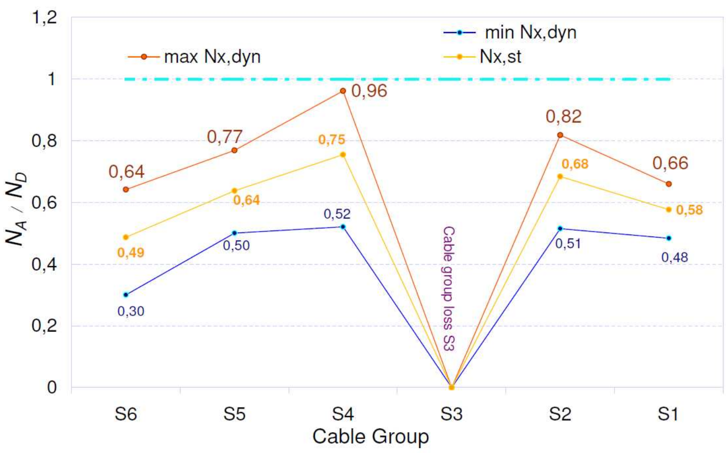

Figure 4. Relation between internal forces caused by sudden cable group loss to design forces in neighboring cable groups

An analog comparison for internal forces in the superstructure reveals different results. Due to the doubling of span-width the bending moments caused by the cable group loss exceed the design values (figure 5). However this quick comparison still underestimates the “true” limit state of failure for the superstructure as the following aspects are not taken into account: The pre-incident static design is based on a large variety of load cases for the final state and often of several intermediate states of construction where higher internal forces often occur. The resulting “design corridors” (e.g. for a bending moment - see figure 5 grey color) are defined by the dominant set of internal forces considering all relevant stress states.

The result of the design is a discrete material distribution in longitudinal direction which can be evaluated by its ultimate strength and compared to the maximized internal forces (see figure 5 red and yellow color).

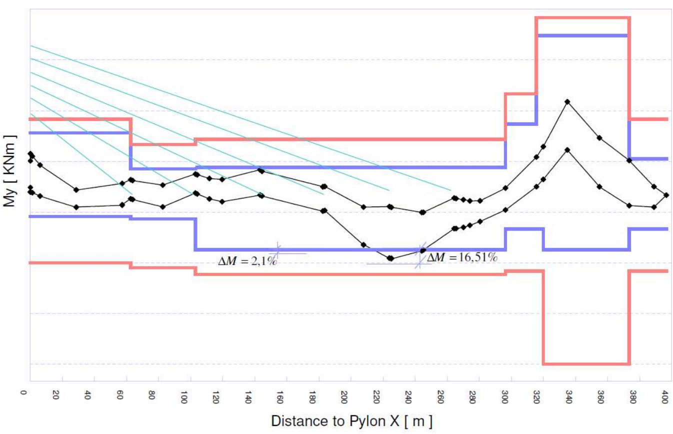

Figure 5. Relation between internal forces (black) caused by sudden cable group loss to design level (blue) and maximum bearing capacity (red) in superstructure

For the exemplary steel bridge superstructure the yield strength of steel is suitable to be considered as a limit state indicating for failure [16], as e.g. the EC3 does not allow for a plasticity approach for closed but slender box girders (Cross-section class 3). However experiments in current research activities show a significant increase in failure load beyond the yield strength [9]. Together with the strain rate effect [25] the ultimate strength of the steel cross section provides bearing capacity reserves which could be taken into account if the yield strength was exceeded. A detailed analysis of the critical cross section in the superstructure with the help of a 3D-Finite-Element Model including local damage caused by an internal explosion (see figure 6) allows for a comparison of the maximized effective stresses and the yield strength of the high strength steel S355 directly.

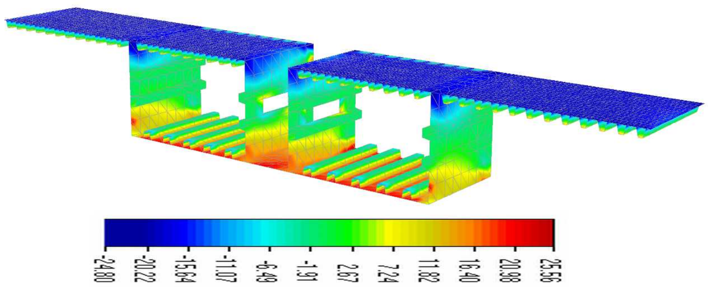

Figure 6. Effective stresses caused by internal forces after a sudden cable group loss – material´s yield strength in example: 35.5 MPa.

The bearing capacity reserves with respect to the global longitudinal loading are quite high. The superposition with additional local forces especially tandem loads lead to an increase of the effective stresses up to 94% of the yield stress. As the yield stress is not exceeded neither by global nor by a superposition with maximized local effects, the superstructure´s integrity is ensured and a progression of collapse does not occur.

The Pylon is also affected by the scenario “sudden cable loss” as it serves as the upper anchorage of the cable groups. The structural dynamic analysis discloses a significant sway of the Pylon (see figure 7) with a maximum deflection amplitude of 0,40 m.

However the maximum deflection caused by static loads is even larger than the structural dynamical effect. A comparison of the maximized stresses with the ultimate bearing capacity of the pylon composite cross-section [15, 17] proves that the pylon is able to withstand the scenario of a sudden cable group loss in the generic example. In contrast to the cable and superstructure the most severe scenario for the pylon is the loss of the upper cable group 1 (see figure 3).

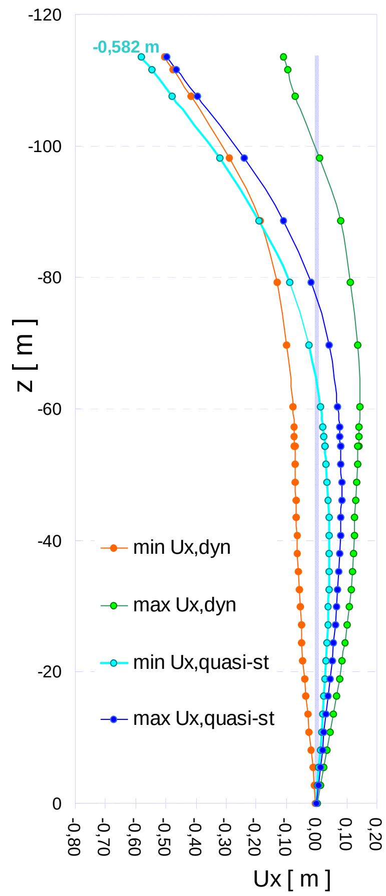

Figure 7. Relation between maximum deflection caused by sudden cable group loss (red, green) to maximum deflection under maximized static loading conditions (blue) for the pylon

After the incident a supplementary post failure analysis is conducted to compute the remaining loading capacity for live loads. It can be shown the structure is capable to carry 60% of the original traffic load at the demanded safety level of permanent and momentary loads (Eq. 1).

6 DEFINITION OF DAMAGE STATE

The damage state of a structure under a specific scenario is technically defined based on the analysis of actions and resistance of the most severe events that potentially occur. The resulting damages are classified in a five step category along the established bridge investigation guideline EBW Prüf [8] and Eurocode 1-1-7 [13] respectively. Table 4 shows the steps and definition for each category.

Table 4 Categories for the definition of damage state [13]

Category	Description of damage state
1	very low
2	low
3	mean
4	high
5	severe

Partial or complete damages require repair, restoration or a complete abridgement and new building.

The overall criticality and vulnerability however can only be evaluated together with supplementary and secondary/indirect effects of damage. A large variety of parameters has to be considered for a comprehensive view. Apart from purely analytical invariant factors a number of subjective variant parameters have to be taken into account. Figure 8 gives an overview over the full set of aspects to be considered to finally generate the overall criticality.

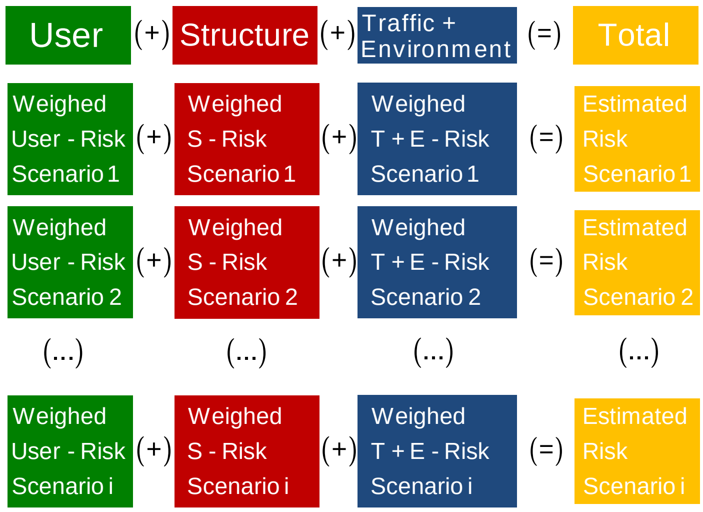

Figure 8. Matrix of aspects to be considered for the comprehensive evaluation of criticality

In contrast to the deterministic analysis of man-made hazards with respect to the structure many parameters which influence the overall criticality are determined by the means of risk assessment. The superposition requires weighing factors partially open to the choice of individual priorities [see also 19, 20]. To provide objectivity a sensivity study is implemented.

7 EVALUATION OF MEASURE EFFECTIVENESS

Once a comprehensive evaluation system for the criticality and vulnerability is established, the variety of measures (see table 1) can be evaluated using the same methodology. The implementation of measures result in an adjustment of the category of criticality (see table 3) for the individual scenario. For the exemplary case of a cable group loss initiated by an explosion the following potential measures can be identified in table 1:

- Enlargement of the distance between cable and explosive by a fortification (fence, casing of cables, etc.).
- Strengthening of cables by a protective layer of energy absorbing concrete or micro-reinforced concrete

The impact analyzed in chapter 5 would be categorized between level 2 and 3 without any protective measures. Apart from the local damage to cables, superstructure and bridge equipment and installations the traffic has to be reduced until repair work is finished.

The suggested measures lead to an enormous reduction of damage to the structural elements as current experimental investigations of the Fraunhofer Institute for High-Speed Dynamics conducted in context with the presented research program show. The intensity of impact forces caused by an explosion is reduced exponentially with increasing distance to the structural component. The strengthening of the cables provides significant supplementary damage mitigation [26]. As a consequence the loss of a cable group can be excluded reducing the damage and thus the category of criticality to level 1.

Apart from these comparatively cost-efficient methods of the direct protection of stay cables and related anchorages, the adjustments of design methods in normative regulations are also potentially appropriate to reduce the damage category significantly.

Either the direct strengthening of cables or the design of a dynamic loading case “cable group loss” with potential measures: alternate load path, enhanced robustness) are suitable to enhance the bridge resilience and lead to a robust structure. A comprehensive evaluation algorithm is developed within the forthcoming work in the research project to compare such measures in an objective way.

8 CONCLUSIONS

The research project SKRIBT (Protection of critical bridges and tunnels in the course of roads) is concerned with the development and demonstration of a comprehensive methodology for the evaluation of infrastructure subjected to severe natural and man-made hazards. The presented paper is focused on the resilience of bridge structures as a part of this general analysis and the relevance and efficiency of protective measures under severe loading conditions.

Starting with a thorough investigation of potential and available measures and an identification of relevant scenarios the extraordinary loading cases are integrated in the semi-probabilistic design approach provided in the current Eurocode standards. The subsequent analysis of those actions and structural resistance is demonstrated by means of a stay cable bridge example.

Albeit the loss of a single cable has to be taken into account in regular bridge design neither the loss of a cable group nor the significant additional dynamical effects possibly caused by man-made hazards are covered in European standards. The presented analysis shows that this scenario does not necessarily lead to an abrupt failure or progressive collapse of the global structure as detailed analysis of maximized dynamical internal forces shows. The analysis is based on safety factors analog to the extraordinary load combination in Eurocode 1 and compared to the materials´ yield strength. Against this background the components remain linear elastic. It can be shown that damage stays localized and only local damages caused by the explosion have to be reconstructed. The resulting bearing capacity limits the allowable traffic loads to 60% of the original loads until the bridge is fully restructured.

The described damages are classified in a five step categorization of damage and evaluated in a comprehensive approach together with all relevant affected aspects for the user and the environment.

Once the comprehensive evaluation system for the criticality and vulnerability is established, the variety of measures (see table 1) can be evaluated using the same methodology. Thus the procedure enables for the evaluation of the relevance and efficiency of protective measures for bridge structures under severe loading conditions.

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