Combining experimental and numerical methods for the safety evaluation of existing concrete structures

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ABSTRACT: The conventional safety evaluation of structures requires input data concerning the current properties of the structure and concerning the mechanical boundary conditions. If this precondition can not be met, experimental safety evaluation including test loading has proved to be a useful and in some cases the only alternative. In numerous cases a combined application of experimental and numerical methods is required. By numerically simulating the fracture process of the investigated structure, decision support for the planning of the actual loading is provided and after the test the experimental results may be extrapolated in order to predict failure mode and ultimate load level. For obtaining realistic numerical results, crack propagation is taken into account by using approaches of non-linear fracture mechanics. The concept of experimental safety evaluation is described and examples for bridge testing are presented.

Keywords: safety evaluation, bridges, loading test, fracture simulation, smeared cracking

1 CONCEPT OF EXPERIMENTAL SAFETY EVALUATION

1.1 *Objectives*

The analysis of structures for the purpose of safety evaluation is possible only if the current geometric and material properties of the structure as well as the mechanical boundary conditions are known. These preconditions can not always be met, especially not in the case of existing structures. Possible reasons are an incomplete documentation, unknown effects of structural faults, and uncertainties in the modeling of the structural system with the appropriate boundary conditions. In such cases, additional data may be obtained by materials testing and by measuring the exact structural geometry. If the required proof of structural safety still can not be provided by analytical means, it is in certain cases worthwhile to determine the structural safety experimentally by performing an in situ loading test. This, however, has to be done without causing any damage which would impair the safety or the durability of the structure.

During the last decade, the technology of the in situ experimental safety evaluation of structures has been significantly improved and extensively tested. A research team of the Bremen University of Applied Sciences, the Technical University Dresden, the Leipzig University of Applied Sciences and the Bauhaus-University Weimar dealt with the experimental safety evaluation from 1992 through 2001 (Steffens 2002). Methods and equipment were significantly improved in this project. Furthermore, the team contributed to the formulation of a technical recommendation for loading tests (DAfStb 2000). The guideline contains the safety concept and technical rules for loading tests as well as criteria for critical load levels. According to the guideline, the experimental safety evaluation by loading tests should be limited to cases where analytical approaches appear to be not applicable for proofing an acceptable safety level.

By using state-of-the-art measuring equipment the research team could successfully evaluate the structural safety and serviceability of approximately 300 structures (Steffens 2002).

By experimental safety evaluations very often additional resistance reserves are revealed which can not be shown by structural analyses, especially in the case of concrete or masonry structures. This is caused by the characteristic properties of these materials varying over a wide range as well as by the boundary conditions which are difficult to model for such structures. In numerous cases, the costly and time consuming replacement of structures could be avoided by experimentally proofing the structural safety. Furthermore, on the basis of the experimental results maintenance and restoration measures may be planned in a more efficient way.

1.2 *Safety concept*

A generally accepted procedure is imposing test loads on the structure and simultaneously monitoring the load-carrying behavior, especially deformations and crack formation. On the basis of the measurements taken, a critical load level may be identified, which is characterized by the beginning of damage processes. This critical load level must not be exceeded in the loading test. In order to avoid damage to the structure, state-of-the-art loading and measuring devices as well as an experienced crew are required. The maximum test load level reached in the experiment is considered a limit load which taking into account a certain safety margin leads to the allowable service load for the corresponding structure.

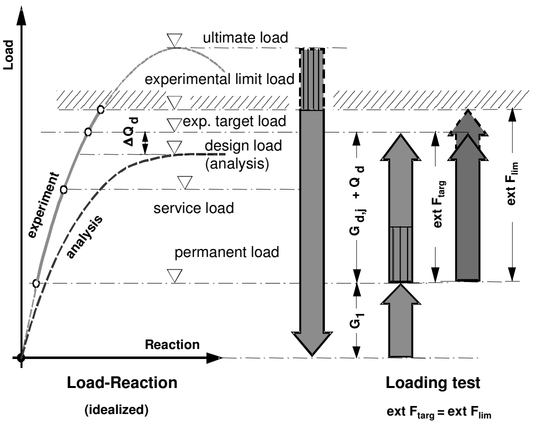

Figure 1. Safety concept of loading tests (Gutermann et al. 2003).

Figure 1 shows the safety concept of loading tests (Steffens 2002). In the load-reaction curve, usually the experimental results reveal a higher stiffness of the structure as compared to the one obtained by structural analysis. Before the loading test, an experimental target load is calculated which corresponds to the design load level including live loads Q_d and additional permanent loads $G_{d,j}$. Different safety factors may be used for the several load types following the concept of load and resistance factor design. A portion of the permanent loads G_1 is already acting before test loads are applied. These loads, mostly resulting from the self-weight of the structure, need not to be simulated in the experiment. During the test, the load-carrying behavior is monitored and the critical load level is identified which marks the beginning of irreversible damage processes. This load level ext F_{lim} is called the experimental limit load. If it is lower than the experimental target load the experimental safety evaluation is considered to be unsuccessful. In the other case, the experimental limit load will not be reached in the experiment and sufficient structural safety is proved.

1.3 *Generation of test loads*

The experimental safety evaluation without causing any damage is tied to two important technical prerequisites:

1. The application of the test loads has to be undertaken in such a way that sudden failure of the structure is avoided even in the case of unexpected fracture processes.
2. During the test loading, the behavior of the structure has to be continuously monitored and evaluated in real time. In this way, critical load levels are detected and the loading program may be altered in order to avoid damage to the structure.

By these measures, the state of the structure is preserved and the safety of test equipment and crew is ensured. Consequently, gravitational loads are not applicable in such experiments. Placing weights on a bending structure involves a considerable risk. If, however, hydraulic actuators are used and a steel frame serves for transferring the reaction forces to the supports of the bending structure, see Figure 2, the loading system is self-securing (Steffens 2002). In the case of unexpected damage, the stiffness of the structure will decrease resulting in reduction of the test loads. Figure 2 shows a reaction frame placed on a concrete ceiling. The frame is anchored near the supports and hydraulic jacks are acting between structure and reaction frame.

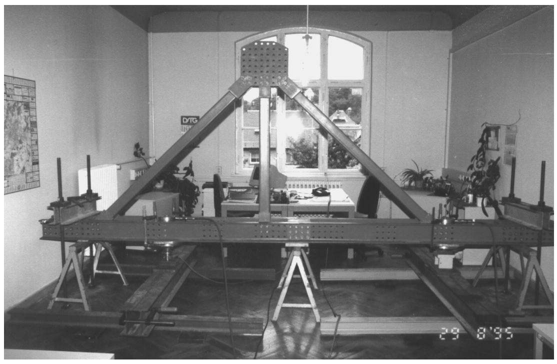

Figure 2. Loading system for testing a concrete ceiling.

A similar procedure for generating test loads has been used for bridges. The construction of the required reaction frames is expensive and time consuming. Test loading by gravitational forces would be technically easier, but is not considered to be an acceptable alternative. For safety reasons, the load level reached in this way should not exceed the service load. Consequently, by using gravitational loads only, an experimental safety evaluation following the concept presented in Figure 1 is impossible.

For performing loading tests at road bridges in a more effective way, a special loading vehicle named BELFA has been designed and built which allows one to conduct these experiments without the cost and time consuming construction of reaction frames (Steffens, Opitz, Quade & Schwesinger 2001). It is registered as a special vehicle and may be moved on public roads, see Figure 3. In its operation mode, the BELFA serves as a reaction frame, see Figure 4. For that, the vehicle is extended and lifted up by using four hydraulic supports, two in the front and two in the rear. The maximum distance between these supports amounts to 18 m which limits the span of the bridges to be tested to this length. After lifting up the whole vehicle, its complete self-weight may be activated as a reaction force for the test loads which are generated by up to five hydraulic actuators. The maximum total test load amounts to 1500 kN. Position and magnitude of the individual forces generated by the actuators are variable. In this way, different live load arrangements may be simulated according to the valid design codes. The BELFA has a self-weight of about 700 kN. If this load is not sufficient for compensating the applied test loads, additional ballast weight is used or the BELFA is anchored at the bridge supports.

Testing a one-span bridge will not last longer than about one day. This results in considerably shorter road closing times. The installation of the sensors for measuring the reactions of the structure requires additional time. However, the traffic flow on the bridge is not influenced by this work. In the control cabin at the rear of the vehicle, the measuring devices are installed and two engineers control the experiment from there. For monitoring the structural behavior under test loads, acoustic emission analysis has proved to provide valuable information. Especially in the case of concrete structures, this method allows very sensitive crack detection. Since 2001 the BELFA has been successfully used for testing about 20 bridges (Slowik et al. 2002).

Figure 3. Loading vehicle BELFA in transport mode.

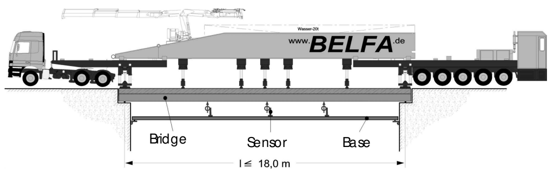

Figure 4. Loading vehicle BELFA in operation mode (Steffens et al. 2001).

Experiences with the loading vehicle BELFA designed for testing road bridges led to the adoption of this technology for concrete and masonry railway bridges. A research team of the Universities of Applied Sciences in Bremen and Leipzig, Germany, with the participation of the Deutsche Bahn AG developed a prototype of a railway loading vehicle BELFA-DB for testing bridge structures (Knaack et al. 2003).

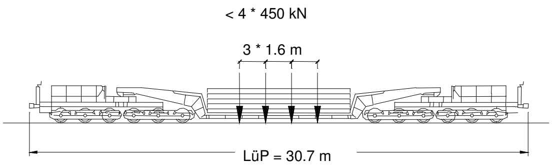

Figure 5. Loading vehicle BELFA-DB (Knaack et al. 2003).

The BELFA-DB consists of a standard railway wagon loaded with steel plates, see Figure 5. Because of its twelve axles a moderate axle load of about 21 t allows moving the vehicle to the test site on normal tracks. If necessary, the transport weight of the wagon may be reduced by unloading it. As in the case of the BELFA for road bridges, the self-weight of the vehicle acts as a counter-force for the test loads. The latter are applied by eight hydraulic jacks, four at each side of the track. In order to prevent damage to the rails, steel girders are used for distributing the loads. Since the bending stiffness of the wagon's main girder is too low for the purpose of transferring the reaction forces, the ballast steel plates are used for strengthening the

cross section. For that reason, the plates had to be tightened together by using steel bars.
The BELFA-DB prototype currently used is applicable up to a bridge span of approximately 15 m. This range covers about 80 % of all German concrete and masonry railway bridges.

Usually, the test load is acting on four simulated axles, see Figure 10, having a distance of 1.6 m according to the standard railway load set UIC 71. The total maximum load which may be generated by using the current prototype amounts to 1800 kN.

Since 2001, the BELFA-DB prototype has been used for testing several railway bridges (Knaack et al. 2003). All these projects were considered to be successful. As far as the measurement of structural reactions due to test loads is concerned, for the railway bridges the same methods and sensors as in the case of road bridges may be used. However, investigating the dynamic structural response appears to be more important for the railway bridges.

1.4 *Numerical simulation of the loading tests*

Experience has shown that especially for solving more complex problems a hybrid approach combining experimental and numerical methods is required. A realistic numerical simulation of loading tests is necessary for the following reasons:

- Determination of the test loads to be applied in the experiments.
- Evaluation of the risk of unexpected damage to the structure due to the test loading.
- Extrapolation of the test results above the load limit reached in the experiments.
- Realistic analysis of load cases different from those applied in the experiments.

In order to obtain realistic simulation results which may be compared to the experimental findings, concrete cracking has to be taken into account. The smeared crack approach of nonlinear fracture mechanics appears to be suitable for this purpose. Usually, the simulations are performed as part of the planning process, i.e. before the actual test. After the test, the analysis may be repeated with updated input parameters in order to match the experimental findings. In this way, a realistic and experimentally supported mechanical model of the structure is obtained.

The program ATENA, Cervenka Consulting Prague, has proved to be a suitable software tool for the analyses to be performed in conjunction with the experimental safety evaluation. Generally, a non-linear stress-strain curve under compression and smeared cracking under tension including softening are assumed.

In the analyses, problems result from unknown material properties for the bridge structure as well as for the soil. In most cases, these parameters may only be estimated by comparison of numerical results to experimental findings during the loading test. Even extensive materials testing would not provide a reliable data base for the spatially varying elastic and fracture mechanics properties needed for the non-linear analysis. It has been found that the effects of strength values, especially of the tensile strength, on the simulation results are significant, whereas the influence of the assumed softening behavior is only moderate.

The usage of 2D models for simulating the behavior of 3D structures causes additional problems in some special cases. Despite these limitations of the fracture simulation described here, this type of analysis proved to be a valuable tool for interpreting experimental observations. The simulation results are far more realistic than those obtained by conventional analysis methods.

In the following section, two examples for a combined experimental and numerical safety evaluation are presented. The second example is a masonry railway bridge. For such structures, the same analysis procedure as for those made of concrete may be used.

2 EXAMPLES

2.1 *Test of a road arch bridge*

Figure 6 shows the BELFA on a historical two-span arch bridge built in 1912 in the German province of Saxony. This bridge has been severely damaged during a flood catastrophe in 2002. Pavement and parapet were partially missing. In addition, the effects of the flood on the actual arches and on the substructure were unknown. Therefore, the bridge had to be closed for security reasons. In order to avoid demolition of the structure an experimental safety evaluation was undertaken.

The usage of the loading vehicle BELFA required a thorough preparation. The self-weight of the BELFA front part was expected to impose a considerable load on this bridge with unknown damage level. Furthermore, a comparably brittle failure mode had to be considered for this structure. Before the actual test, the effect of the three BELFA front axles passing the bridges was estimated by means of non-linear numerical analysis. Figure 7 shows the 2D Finite Element model with loads resulting from the three BELFA front axles.

Several combinations of material parameters for structure and soil were assigned to the model. It

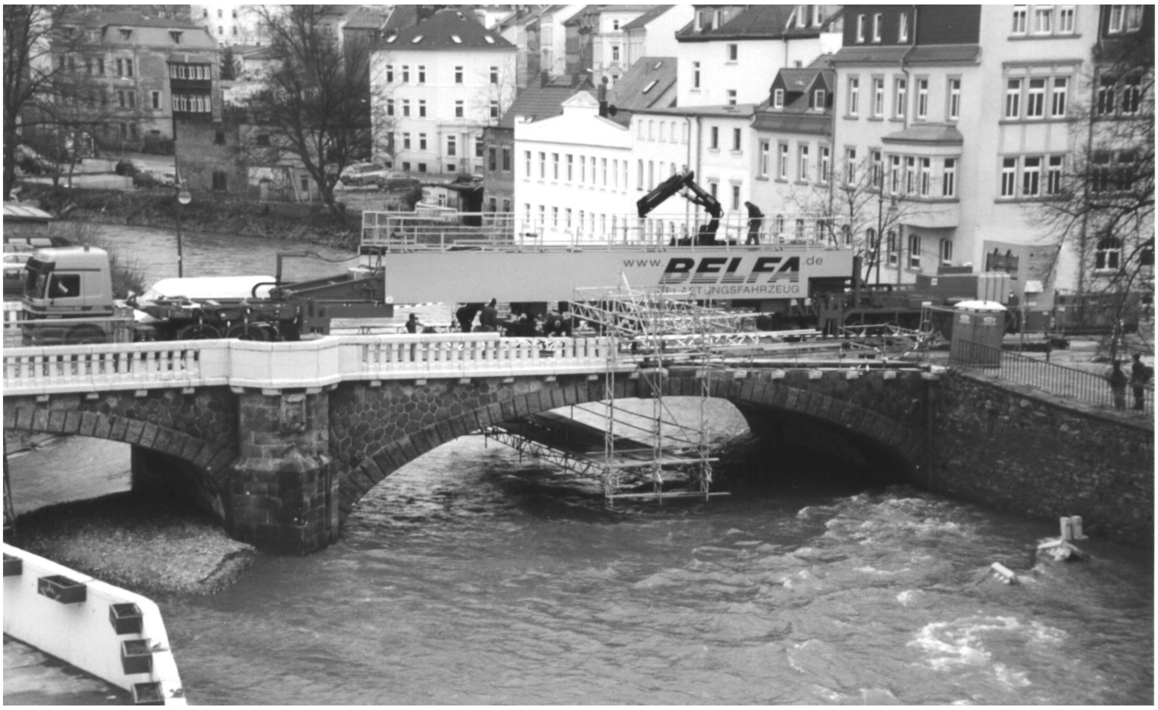

Figure 6. Loading test at a historical arch bridge by using the loading vehicle BELFA.

was concluded that, in the worst case, cracking occurs close to the supports, see Figure 8. In this way, hinges are formed which do not reduce the structural safety and may be accepted. The distances between the cracked regions correspond to the span values specified in the original design drawings, 17 m and 13 m. Probably, such cracks were formed already during the preceding service life of the bridge.

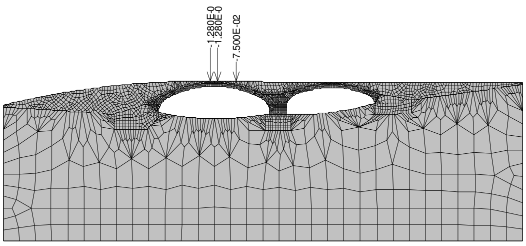

Figure 7. Finite Element model of the road bridge, see Figure 6.

Figure 8. Obtained crack pattern under the load of the BELFA front part.

By the fracture simulation it could be shown that the structure is likely to withstand the loads imposed by the BELFA front part passing the bridge. Hence, the actual loading test could be carried out. The placement of the BELFA on the bridge as well as the loading test itself were carefully monitored by using numerous strain and displacement sensors. In addition, multi-channel acoustic emission analysis was used for crack detection. The numerical results could be confirmed, i.e. the measured strains were within the range of the predicted values obtained in the analyses under different assumptions for the material properties. As in the fracture simulation, no midspan bending cracks occurred.

The interpretation of the experimental results required the usage of the numerical model, now corrected on the basis of the experimental findings. Safety levels for different bridge classes, specified in the technical design codes, could be determined by comparing simulation results obtained for the design code loading to those obtained for the test loads applied in the experiment.

On the basis of the results of the loading test and of the analyses it was decided to maintain this historical arch bridge. However, for meeting future requirements the structure needs to be strengthened. Having now an appropriate model of the bridge, it is possible to estimate the effects of temporary loads during the restoration work, for instance of those resulting from machinery or fresh concrete.

2.2 *Test of a railway arch bridge*

The bridge under investigation has a clear span of 4.32 m and was built in 1849, see Figure 9. It supports two tracks and has a width of 9.61 m. The masonry arch with a thickness of 0.58 m is the major structural element. A conventional analysis of the bridge pointed to an unsatisfactory safety level and it was decided to perform an experimental safety evaluation. Furthermore, the effect of minor damage on the load carrying capacity was expected to be evaluated more realistically by experimental means.

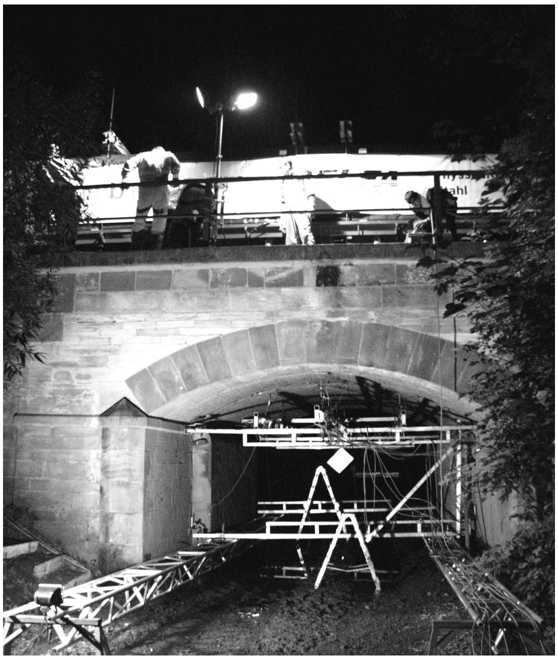

Figure 9. Loading vehicle BELFA-DB on a railway bridge.

According to the technical railway code UIC71, four test loads with a distance of 1.6 m were applied on the track located on the assumed weakest side of the arch bridge. The maximum total test load amounted to 1800 kN. For monitoring the structural behavior the bridge was instrumented with numerous displacement and acoustic emission sensors. The critical load case appeared to be a symmetric arrangement of the four test loads with respect to the arch key. During the loading test, no new cracks were detected and only moderate tensile strains at the down side of the arch were measured.

For obtaining a better understanding of the structural behavior, the measured results were extrapolated by means of a Finite Element simulation. The mesh is shown in Figure 10. A major limitation of this analysis results from the 2D modeling of a 3D problem. In the actual experiment, the load was applied asymmetrically with respect to the bridge axis. This results in an underestimation of the deflections in the numerical analysis. Whereas in the real experiment a midspan deflection of about 0.8 mm has been measured under maximum test load, the corresponding value obtained numerically by using the 2D model amounts to 0.51 mm. As in the experiment, under the test load of 1800 KN no cracking occurred in the arch.

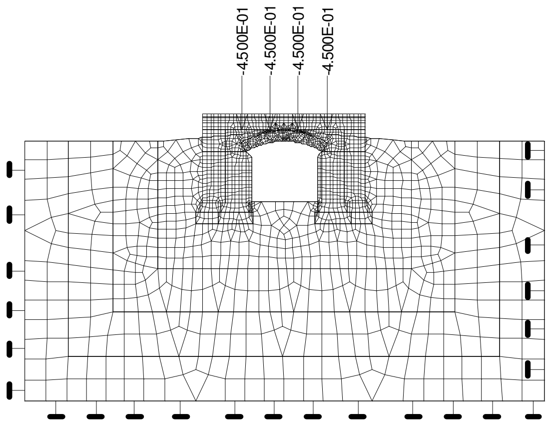

Figure 10. Finite Element model of the railway bridge, see Figure 9.

In parametric studies for this particular arch bridge, only a moderate influence of the soil stiffness was found. This is probably due to the comparably strong substructure. Usually, the soil stiffness has a significant influence on bridge deformation and ultimate load. In order to be on the safe side, the modulus of elasticity for the soil was set to a small value of 111 MN/m² under plain strain conditions.

A very low modulus of elasticity was assigned to the face walls on both sides of the bridge in order to be conservative. By doing this, the effect of the face walls on the load carrying behavior is reduced.

In other numerical simulations of arch bridge failure, fracture processes in the face walls sometimes caused numerical problems. After the formation of large cracks in these walls or in the interface to the arch, convergence problems occurred although the arch as the main structural member had not reached its ultimate load level yet. The finite element results, including the crack patterns, need to be evaluated carefully in order to avoid incorrect interpretations. By varying input material parameters for structure and soil the different influences on the fracture behavior may be estimated and a better understanding of the failure process is obtained.

Full self-weight of all parts of the structure, but not of the soil, is taken into account here. The four test loads were applied directly on the arch. A set of input material parameters has been adopted on the basis of known material properties and common assumptions. For the tensile strength of the arch material 0.1 N/mm² was assumed. After comparing the measured structural response to the numerical results some input parameters were corrected.

In the following description of the simulated fracture process only cracks with a minimum opening of 50 µm are considered. First cracks occurred at a total load of 3000 KN, in the arch key at 3500 kN. The ultimate load found in the analysis amounts to 4000 KN. Figure 11 shows the final crack pattern. In addition to the bending cracks on the down side of the arch there are inclined splitting cracks due to compressive forces.

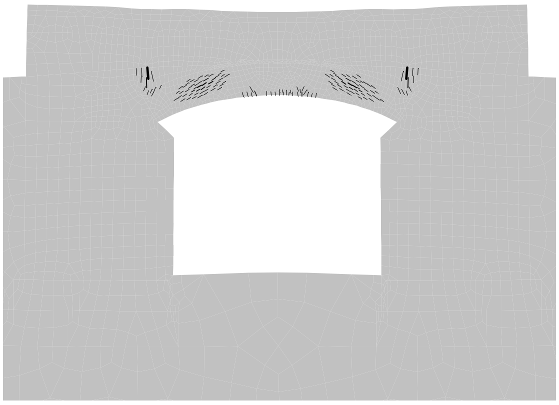

Figure 11. Obtained crack pattern under ultimate load.

In the loading test, sufficient structural safety of the bridge could be proved. In the extrapolating numerical analysis of the experiment, an even higher ultimate load level was reached. However, in the experiments another structural problem was identified. The load carrying capacity of the bridge seems not to be limited by the arch failure but by the stability of the head walls to the left and to the right of the bridge.

3 CONCLUSIONS

The experimental safety evaluation of structures appears to be a technical alternative if analytical approaches fail to prove sufficient structural safety. Numerous concrete and masonry structures could be rescued from demolition by loading tests and financial as well as environmental resources for their replacement could be saved. During the last decade, the technology of in situ structural testing has made significant progress (Steffens 2002). Results of this development are special mobile loading devices for road and railway bridges (Steffens et al. 2001). Their usage allows conducting the loading tests more efficiently.

In many cases, a reliable safety evaluation is possible only by the combination of in situ loading test and numerical simulation. The latter requires a realistic modeling of the material behavior including cracking. The smeared crack approach of nonlinear fracture mechanics has proved to be applicable for this purpose. Numerical simulations are used as planning tools for the actual loading test and allow interpreting the experimental findings afterwards.

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