Confirmation of limit state design of impact and impulsive loaded RC-structures by large scale testing

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1 Introduction

The confirmation of the limit state design of reinforced concrete (RC-)structures against impact or impulsive loading has to deal with two levels of engineering mechanics.

In a first step, it has to be evaluated, which phenomena occur or dominate under certain circumstances. In a second step and with respect to the results of the first step, the details of a design-procedure have to be treated and the necessary assumption must be defined.

The first step task can only be solved in large scale experimental investigations as have been done in the "Meppen Tests" [1]. They are the basis of the distinction between "soft missile impact" and "hard missile impact" (Terminal Ballistics). Being concerned with the second task, one has to follow up the dominant mechanism as resulted from the first step investigations. There are strain rate and strain rate history effects in addition to quasi-static materials behaviour approach. In BAM, we were concerned with this aspect in large and medium scale experimental investigations.

2 Mechanical design basis

The fundamental simplification in the design procedure for RC-structures under aircraft crash is the shifting of the two-bodies-impact problem to a local impulse problem, fig. 1. This holds if the structure withstands the load with only relatively small deformations and is the so-called "soft missile impact" approach [2]. The "Meppen Tests" verified this concept [1] [2].

The mechanical laws of conservation - conservation of mass, momentum and energy - are a commensurate basis for the treatment of all the problems in this type of "collision dynamics" [2].

In connection with advanced numerical methods a solution close to the reality should be possible. However, the very simple material models used up to now, are not sufficient to

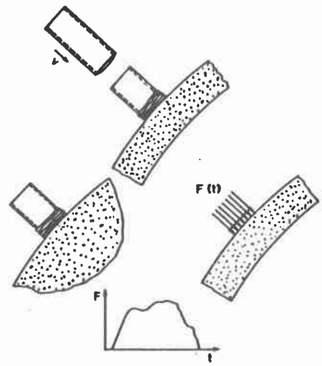
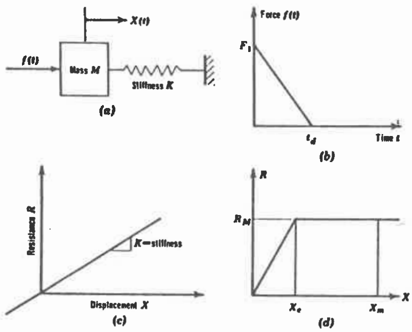
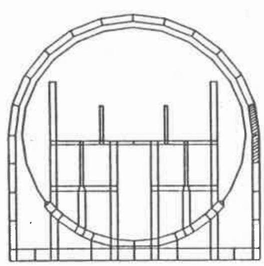


Fig. 1. Impact Phenomena: Soft missile impact. Crushing of a plastically deformable missile on a very stiff structure. Decoupling of the problem.



Single-degree-of-freedom system: (a) system schematic; (b) triangular impulse load time history; (c) linearly elastic resistance function; (d) elasto-plastic resistance function

Fig. 2. Simplified mechanical models for analysing the behaviour of structures impacted by a deformable body (from [4])



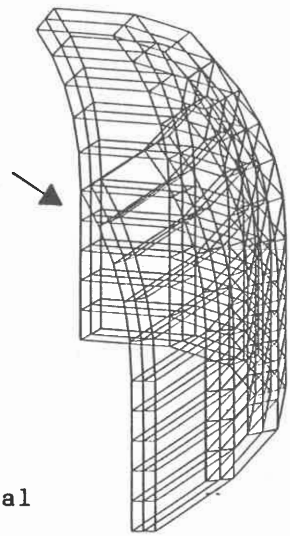


Fig. 3. Example for the application of detailed computer analysis techniques:
Discretisation of a NPP-containment structure to calculate the structural response to aircraft crash [8]

enable such results. Strain rate effects and strain rate history effects appear and lead to large differences between calculated and observed response of RC-structural members to impact and impulsive load [2]. Consequently, more sophisticated constitutive laws for the material behaviour have to be established and confirmed in tests.

3 Analysis and design-criteria

The mechanical behaviour of reinforced concrete structural members under soft missile impact or impulsive load is governed by the same phenomena as appearing under static load. In experimental investigations this type of behaviour is called "high speed static testing", in contrary to "high speed dynamic testing", which appears if stress wave motion governs the mechanical behaviour [3].

There is a broad variety of analysis methods for impulse load, simplified ones on the one hand, fig. 2, and the detailed computer analysis techniques on the other hand, fig. 3. They are presented in many journals and textbooks. The manual [4] outlines some of the simplified methods, which are very helpful in many cases, if mainly the fundamental understanding of the behaviour of mechanical systems is searched.

The design criteria includes deformation limits as well as stress limits which are known from static loads. The severe local nature of impact load desires a design, which utilizes localized plastic deformation to absorb the energy input by the loading. Therefore, all design methods and criteria are concentrated on inelastic behaviour.

While in some codes deformation limits are specified in terms of allowable ductility ratios [4], in a few codes deformation limits in terms of allowable strains or rotation in plastic hinges are established [5] [6]. A comparison of deformation limits evaluated from tests [2] and allowable ductility ratios laid down in the manual [4], shows some discrepancies. In a revision of the codes, it should be refered to quite recently completed tests [6].

One of the most dominant characteristics of soft missile impact is the sensitivity of the deformation of the mechanical system under consideration to small changes in the characteristic values of strength of the impact RC-structure. This sensitivity originates from the energy transmission in the critical region of impact contact zone. Mostly, a big amount of the kinetic energy of the impacting deformable body is absorbed in the striking body by large plastic deformations generating a considerable rise of temperature. Only a very small portion of the kinetic energy is transmitted to the RC-structure. But, if the RC-structure starts to move plastically at the point of impact, there is energy enough to deform the RC-structure up to its limits and even more which leads to penetration. Thus, energy absorption capacity of RC-structural members in comparison with the kinetic energy of the missile can not be used as a criterion in the design process. But a large energy absorption capac-

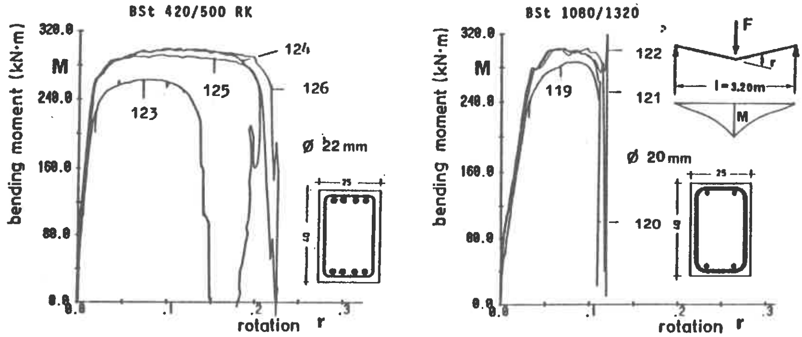


Fig. 4. Influence of strain rate on the characteristic curve of a plastic hinge in a RC-beam (reinforced with different types of steel [2])

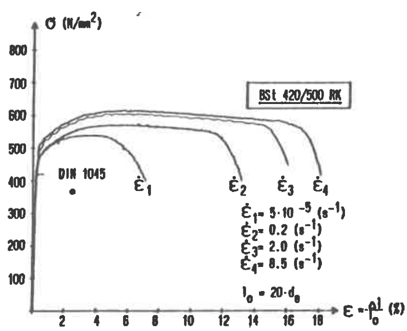


Fig. 5. Influence of strain rate on the stress-strain-curve of cold-worked ribbed reinforcing steel [2]

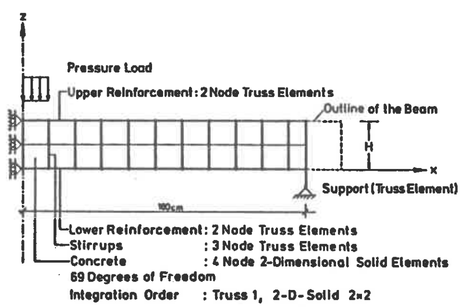


Fig. 6. Finite Element Model on one half of the symmetric RC-beam

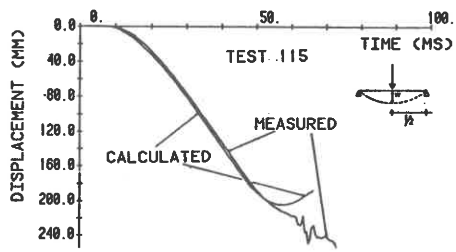


Fig. 7. Midspan displacement-time curve for a RC-beam

ity should be reached in the design to avoid a strong sensitivity of the structure to relatively small variations of the load-time-curve.

4 Results from experimental investigations

The tests in BAM were performed on similar specimes - RC-beams, RC-slabs and reinforcement bars - under different rates of deformation or straining, covering the range from "static" loading (that means: 0,1 mm/s) up to impact-like conditions (about 5 m/s). As a result, there are available the characteristic values of strength and fracture elongation as a function of strain rate, fig. 4 and fig. 5 [2] [8] [9].

5 Results from computational investigations

The major aim of the investigations in BAM was, to improve the knowledge about the material behaviour such, that the behaviour of a tested RC-structural member could be "synthesized" by a computational investigation.

Between test results and design requirements should be a close interaction. Design requirements are often formulated by assuming a specific model idea. For example, the rotational angle is related to the "yield line" or "plastic hinges model" or the strain or curvature is related to a plane cross-section model or the shear stress is related to a shear cone model. In many cases it is possible to analyse tests on beams and slabs assuming different models if the required data could be measured. It might happen that some tests show phenomena that could not be modeled in the usual design model. New models have to be evaluated for this task or known models have to be modified. The reliability of the new model can be confirmed by comparision of test results with the results of computational investigations. For that reason, a numerical analysis of some RC-beams has been performed at BAM [10]. The Finite-Element-Code ADINA was used. Fig. 6 shows the FE-model used in the nonlinear dynamic analysis. To take into account strain rate effects, the concrete strength and steel yield stress was increased in comparison with static values. The increase of the steel yield stress was according to the results from our tension tests. The procedure is only an engineering approach. As shown in fig. 7 the computed midspan-deflection-time curve of that simple example is in good agreement with the experimental curve. For complex structures and load histories a great need for improved formulations of material models considering strain rate effects or even strain rate history effects exists. The confirmation of those models requires further difficult experimental investigations. The material model used in the FE-model is based on the input of a stress-strain relationship. Other models are possible using a moment-curvature relationship or a moment-rotational-angle relationship in the evaluation. It is obvious that the model used for analysis of the tests has to correspond to the model used in design. Another aspect is that in design often different models are needed to represent reality, for example, one for the flexural behaviour and another for punching shear mode. The idea on how to formulate reliable design models sometimes results from a precise analysis of tests.

It should be mentioned that numerical analysis of slabs failing in punching shear after plastic flexural deformations ("secondary punching shear") have been performed by applying an endochronic material theory [9].

6 Concluding remarks

The results of the tests on RC-beams, RC-slabs and reinforcing steel show that a reliable design of impact loaded reinforced concrete structures is only possible taking into account the observed phenomena. This means that tests are inevitable to observe the principle mechanism and to get reliable material data. If tests on natural size members are not possible, the reality has to be modeled in suitable tests on smaller specimens. For the evaluation of the tests advanced mechanical models are requested which can describe the dominant observed effects.

In case of impact loading of RC-structures design models based on static considerations are often insufficient. Furthermore strain rate effects or even strain rate history effects have to be included. A full consideration of all observed significant effects is not possible up to now. Therefore, more or less engineering approaches are requested which have to be verfied in tests. Finally, it can be stated that there is a close interaction between tests and design models and both should be in good agreement with reality.

REFERENCES

[1] Jonas, W., Rüdiger, E. u. a. Kinetische Grenztragfähigkeit von Stahlbetonplatten. IV. Technischer Bericht (Schlußbericht) zum Vorhaben RS 165, Hochtief AG - Frankfurt.

[2] RILEM-CEB-IABSE-IASS-Interassociation Symposium. Concrete structures under impact and impulsive loading, Berlin (West), June 2-4, 1982. Introductory Report, BAM, 1982; Proceedings, BAM, 1982.

[3] Grimminger, H.. Probleme der Materialprüfung bei zerstörender Beanspruchung unter hohen Verformungsgeschwindigkeiten. GIT Fachzeitschrift für das Laboratorium 1968 (S. 1282-1292) und 1969 (S. 1-9).

[4] Structural analysis and design of nuclear plant facilities. American Soc. Civil Engineering, New York, 1980.

[5] Code requirements for nuclear safety-related concrete structures. Proposed ACI Standard 349, 1976.

[6] KTA 2203, draft, Dec. 1983. Protection of nuclear power plants against aircraft impact. Design of buildings (In German).
[7] Brandes, K.. Design of reinforced concrete structures against impact and impulsive loading. 12th Congress IABSE, Vancouver, Sept. 3-7, 1984. Final Report.
[8] Buchhardt, F., Magiera, G., Matthees, W. and Weber, M.. A nonlinear 3D containment analysis for airplane impact.Transaction 7th Int. Conf. SMiRT, Aug. 22-26, 1983, Chicago, Vol. 7, pp. 439-446.
[9] Steberl, R.. Berechnung stoßartig beanspruchter Stahlbetonbauteile mit endochronen Werkstoffgesetzen. Diss. TU Berlin, 1985.
[10] Herter, J., Limberger, E. and Brandes, K.. Experimental and numerical investigations of reinforced concrete structural members subjected to impact load. In: Design of Concrete Structures - The Use of Model Analysis. Edited by Clarke, J.L. et. al.. Elsevier, London and New York, 1985, pp. 168-178.