Testing and Analyzing Reinforced Concrete Structures Subjected to Blast Loads

F. Stangenberg, R. Zinn
Zerna, Schnellenbach & Partner, Consulting Engineers, Viktoriastr. 47, D-4630 Bochum, Germany

W. Junge, D. Stölzl
Hochtemperatur Reaktorbau GmbH, Gottlieb-Daimler-Str. 8, D-6800 Mannheim 1, Germany

SUMMARY

In the Federal Republic of Germany, a current research program deals with the PNP-project (Prototype Plant for Nuclear Process Heat). Within this program, also explosion hazards due to bursting pressure vessels are being studied. Apart from the research on mechanisms, which lead to a pressure wave and apart from the research on finding a TNT-equivalence and on other gas explosion phenomena, one part of the program is related to the investigation of the behaviour of reinforced concrete structures subjected to blast loading. During this part of the program, which is not finished up to now, there have been blast tests in the open air and in closed rooms with typical reinforced concrete structures as plates and frames.
During these tests, the reinforced concrete structures have been subjected to extreme dynamic pressure loads generated by TNT-explosions up to the point of failure. Corresponding numerical analyses were performed in order to predict and recalculate structural responses and to develop non-linear analytical methods.

The paper mainly points out two aspects which turned out during the experiments: The blast tests in the open air, which had extremely short loading times, indicated that the phase of underpressure was of significant importance. The phase of underpressure overlapped with the phase of increasing strains and effected a considerable decrease of the total load. This effect becomes more significant with increasing degree of plasticity because of increasing response periods.

The second important aspect is related to the indoor TNT-explosions: during these tests relatively long pressure-load-functions with high-frequency contents were measured. Smoother functions of much lower amplitude can be derived from the high-frequency pressure functions by supplying filter processes, and these simplified functions are equivalent to the original functions with respect to the dynamic responses of the concrete structures.
The corresponding numerical analyses were performed using computer codes on the basis of numerical integration taking into account non-linear material behaviour. These computer codes can be used to obtain adequate estimates of the structural responses.

1. Introduction

The intention of the tests was to study the dynamic response of typical reinforced concrete structures of nuclear buildings subjected to a blast wave due to a hypothetical explosive failure of a high-pressure steel vessel. General derivations for practical design had to be found out.

2. Blast Tests in the Open Air

These tests referring to the right hand part of the test program chart in fig. 1 were carried out by Messerschmitt-Bölkow-Blohm GmbH (MBB) in Schrobenhausen.

In the tests, the blast wave was generated by a TNT detonation, which was nearly equivalent to a representative case of a bursting pressure vessel with respect to the energy as well as to the overpressure-time function in a certain distance. Thus,

- the distance between the explosive charge and the reinforced concrete structural model and
- the quantity of the explosive charge

were the free parameters to determine the overpressure-time function at the test model surface (TNT equivalent for blast simulation due to bursting pressure vessels). E.g., an explosive charge of 15 kg TNT at different distances resulted in the overpressure-time functions of fig. 2. The time characteristics of the TNT-generated pressure loads should be the same as in the cases to be simulated, i.e. the time characteristics (rise time, periods of phases, frequency contents) should not be changed by the model scale.

The reinforced concrete model structures were intended to be scaled at some 1:2 of the original geometric size, while the natural frequencies were not changed essentially. This led to the following model structures fabricated of concrete B25 and of reinforcing steel BSt 420/500 RK:

Type 1: One-way slab of 10 cm thickness; 2 m span width; simply supported; 0.35 percent of reinforcing steel each face in span direction.

Type 2: Two-way square slabs of 7 cm and 10 cm thickness; 2 m x 2 m; edges stiffened by beams for simulating partially fixed supporting; 0.35 percent of reinforcing steel each way, each face.

Type 3: Portal frame, 2.5 m of height and 2.5 m of girder length; both columns b/d = 25 cm/25 cm; girder: b/d = 25 cm/40 cm; reinforcement designed for a static ultimate yielding resistance against a horizontal load in the girder axis of 70 kN.

The analytically predicted results were based on a nearly triangular overpressure impulse function of the type as the first part in fig. 2 neglecting the underpressure phase following to it. For the load-time diagram designed for, i.e. a diagram consisting of the overpressure phase only, large plastic strains were expected, but did not occur. The pressure loads could be raised considerably, in order to effect critical states of strains and damages.

Recalculations taking into account the total time history of the pressure load including the suck phase, where the integral suck impulse may be about a quarter or more of the overpressure impulse, were much more conform with the test results. As the underpresssure phase, in all tests, was over, before the maximum structural response occurred - this concerns more the low frequency and highly ductile structures as the one-way test slab and especially the test frame (with such structures the highly ductile behaviour effects a longer period of response increase) - the difference of overpressure and under-pressure impulses is the significant parameter. I.e. less than 75 % of the overpressure impulse (reduction by at least a quarter) is effective only.

Further beneficial effects, e.g. a higher structural resistance due to higher material strengths compared with the strengths according to the standards, also contribute to the conservatism of the design based on analytical predictions. Thus, the usual engineering practise for blast resistent structural design based on the overpressure impulse only and on standard material strengths, in the tests, turned out to be conservative by about a factor 2 or more.

3. Blast Tests in Closed Rooms

These tests, once more referring to the right hand part of the test program chart in fig. 1 were carried out by Institut für Chemie der Treib- und Explosivstoffe (ICT) in Pfinztal.

The overpressure-time history acting on a structural surface inside a closed room where multiple reflexions occur was measured e.g. as plotted in figs. 3 and 4. By analytical studies comparing different simplifications for such a complicated load, was found that a filtered load as plotted in figs. 3 and 4 is equivalent with respect to structural design. Both load curves effect the same maximum dynamic structural strains in the structures analysed, see fig. 5. Thus, a corresponding process for simplifying the load input can be recommended for structural engineering practise.

4. Conclusions

From the open-air blast test results, can be derived that the usual structural engineering practise of neglecting the underpressure phase and of taking into account the material strenghts according to the IfBt and KTA regulations leads to highly conservative results.

Evaluations of the indoor blast test results show that rough simplifications of the very complicated load-time history can be done for structural design purposes. By filter processes for eliminating higher frequencies beyond a certain limit, a simple equivalent function remains, which can be handled much more easily.

5. References

/ 1 / Schulte, K., "The Gas Cloud Explosion Program on the PNP-Project", Discussion on Explosion Hazards at the 7th International Colloquium on Gasdynamics of Explosions and Reactive Systems, Göttingen 1979

/ 2 / Stangenberg, F., "Dynamic Ultimate Load Analysis Using a Finite Difference Method", Paper T3/3, ELCALAP-Seminar, Berlin 1975

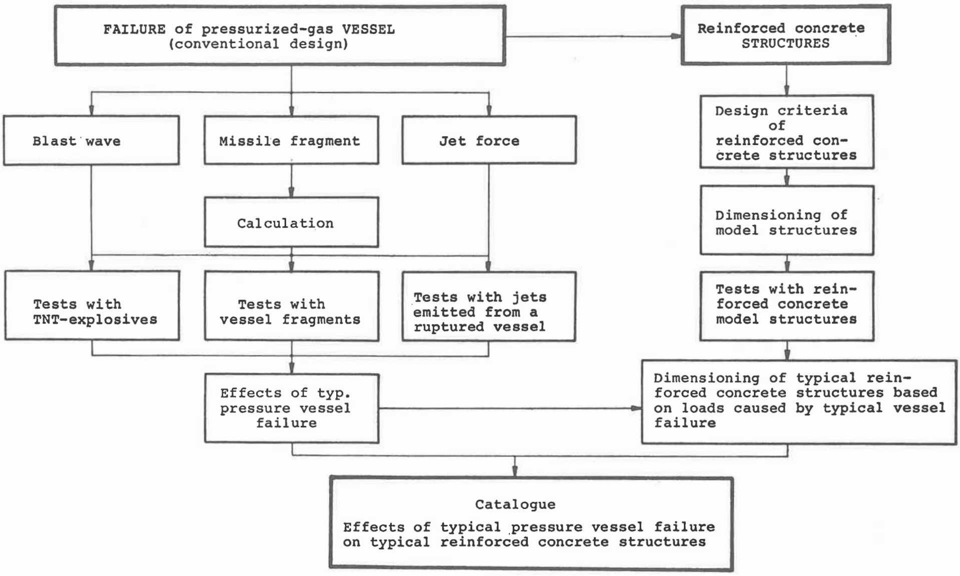

Fig. 1 Test program chart

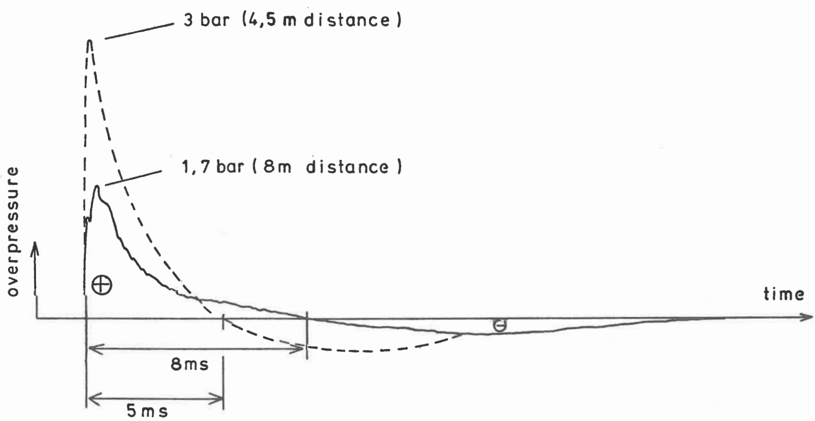

Fig. 2 Overpressure versus time on the test model surface due to a 15 kg TNT detonation

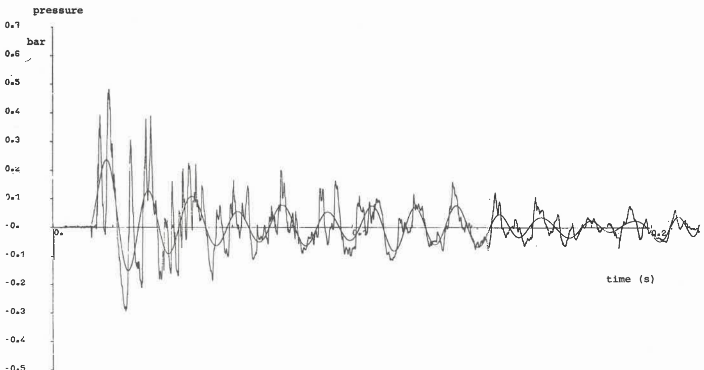

Fig. 3 Measured pressure and filtered function (frequency content up to 100 Hz)

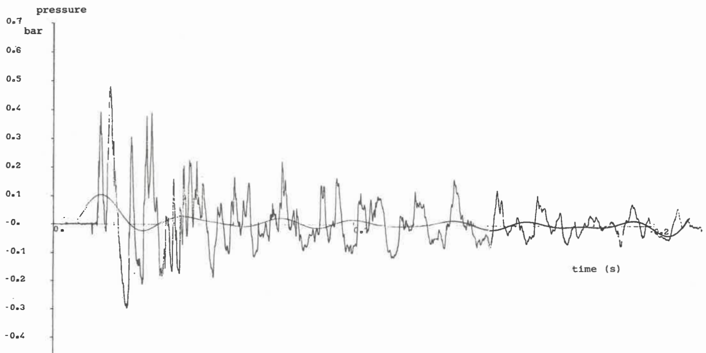

Fig. 4 Measured pressure and filtered function (frequency content up to 50 Hz)

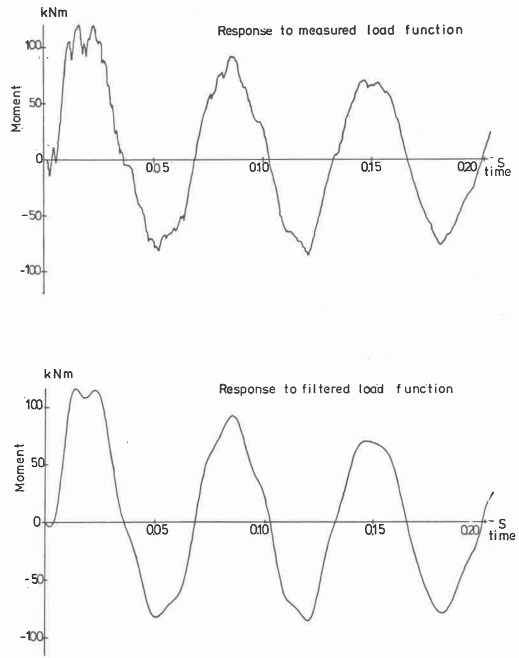

Fig. 5 Bending moment at midspan of the test structure