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Verification of material models for nonlinear calculation of concrete structures during explosive loading

Freund, H.U.[1], Krutzik, N.J.[2], Tropp, R.[2]
1) Battelle Ingenieurtechnik GmbH, Eschborn, Germany
2) Siemens AG, Power Generation Group (KWU), Offenbach, Germany

ABSTRACT: Explosive dismantling tests which had been performed previously at the HDR facility were thoroughly reinvestigated with respect to nonlinear concrete behavior under this type of transient loading. The test body employed was a cylindrical concrete shell of 3.3 m in height, 0.7 m in wall thickness and 4.7 m in diameter, resembling the biological shield of a nuclear power station on a 1:2 scale. The loading was caused by detonating a radially symmetric array of borehole charges. Three such loadings were successively applied to the model shield. The properties of the remaining concrete of the model shield and the surrounding HDR concrete wall were evaluated by material analysis of the concrete and by nonlinear finite element computer calculations. The calculations simulated both the transient loading and the structural and material response. This includes the destruction zone (~10 cm thick), the adjacent zone of reduced tensile strength (20 to 30 cm thick) and the zone of undamaged concrete, where compressive and tensile strengths are practically unchanged. The experimental data are interpreted well over three orders of magnitude of stress values (11 kbar down to 0.1 kbar) employing an improved concrete material model which had been developed previously for less severe loading conditions.

The method of analysis is expected to be applicable also to other transient loading events, e.g. impact or gas explosion. This work has been supported by the German Ministry of Education, Science, Research and Technology under project no. 02S 7482 5.

1 OBJECTIVES

It is of great interest to understand and predict the mode of (desired) destruction of the concrete immediately in contact with a detonating explosive charge as well as the degree of damage inflicted on the remaining structure in the near vicinity.

Within the framework of previous explosive dismantling investigations [1] to [5], a number of concrete specimens were dismantled using various explosive techniques. Most of the test specimens were reinforced concrete slabs measuring 2.0 x 2.0 m with a thickness of 70 cm. The tests were accompanied by pre- and postcalculations. The aim of the original precalculations was to assist in optimizing the distribution and depth of the explosively charged boreholes as well as the quantity of explosive. The aim was to obtain maximum material removal and inflict the least damage on the remaining structure.

The subject of this study was a nonlinear postcalculation [6] in connection with explosive dismantling of a cylindrical test specimen 3.3 x 4.7 m diameter x 0.7 m wall thickness (model shield of a PWR on a scale of approx. 1:2) employing consecutive detonations of radially symmetric explosively charged borehole arrays. The main objectives were as follows:

Determination of the states of strain in the model shield and the HDR inner cylinder following the first detonation, in order to compute (predict) the actual degree of damage and compare this computation with the measurement results.
- Determination of the states of strain following the second detonation in the pre-damaged concrete, in order to compute the break contour in the model shield, as well as the cracking in the inner cylinder.
- Verification of the final state of damage.

2 DESCRIPTION OF TESTS

Three subsequent blasting tests were performed in which a ring layer was explosively removed in each. In order to achieve this, an array of 360 boreholes was used. A preselected number of the holes was loaded with standardized explosive borehole charges and simultaneously blasted in each test. The borehole array in the concrete ring is shown in Figure 1.

In the first test the upper half of the concrete ring was peeled by an array of short horizontal boreholes. In the second test the lower half of the ring was peeled explosively by an array of long vertical boreholes. In both cases a layer of 20 cm of concrete was removed.

In the third test the ring was equipped over its full height with an array of short horizontal boreholes and a layer of 25 cm was removed.

In each of the tests all explosively charged boreholes were ignited simultaneously using precision detonators.. In this way a radially symmetric transient load was inflicted on the concrete ring and transmitted to the remaining structure.

The pressure-time load functions for each borehole had been determined from a combination of previous experimental data and calculation. Such load functions are shown in Figure 2.

3 TRANSIENT MEASUREMENTS

Transient measurements were taken from a variety of sensor types which were embedded into the concrete ring during casting. The following sensors were employed:

Force sensors

Area force sensors using piezoelectric PVDF foil material. These sensors are measured the transmitted force per unit area in the interface between the concrete ring and the HDR structure.

Strain gages

Strain gages were attached to the reinforcement bars within the concrete ring at various positions as shown in Figure 3. Also strain gages were attached to the outer surface of the HDR concrete central column.

Acceleration sensors

Acceleration sensors were also installed on the outer surface of the HDR central column.

Altogether up to 36 sensors were used for transient data recording. The data were used for comparison with calculated results (see Figure 3).

4 POST-TEST CONCRETE ANALYSIS

A total of nine drilled cores of two different diameters (100 mm and 60 mm) were taken from the concrete ring and the HDR central column in order to analyze the material properties. From core sections samples were taken to perform standard compressive and tensile strain analysis. Also selected samples were subjected to crack size and distribution analysis. The bulk material integrity of additional selected samples was analyzed by a new ultrasound resonance technique.

5 MATHEMATICAL MODEL

A partial finite element model representing a 30° section of the ring structure was generated. By using symmetry conditions the total model can be derived from this partial model (see Figure 3, right side). The calculations of the dynamic loading process and concrete response were performed using the finite element program NONDYN. This program also incorporates the nonlinear behavior of materials such as concrete, steel, rubber, plastics and others.

6 MATERIAL MODEL FOR REINFORCED CONCRETE

Some of the main characteristics of the material model are as follows:

- The reinforcement is smeared over the elements according to its local distribution.
- Within each element, steel and concrete act independently, and constant deformations are assumed along the element border.
- The concrete behavior is distributed by sectionally constant compression and shear moduli which depend on the strain velocity and the local stress state.
- Both compressive and tensile stiffening are taken into account.
- Cracks are assumed to occur instantaneously upon a certain tensile strength being exceeded; cracks may occur in all three orthogonal directions.

The stress-strain diagram is shown in Figure 4.

7 CALCULATIONS

In the first calculation, undisturbed concrete was assumed as the initial condition. After the first test, modification of these material laws becomes necessary. Following the first test (horizontal boreholes), the first cracks, and therefore also a change in concrete properties, occurred. Explosive loading was repeated during the second test (vertical boreholes) and third test (horizontal boreholes), resulting in the final condition which is characterized by the crack sizes and densities and the final state of deformation.

In accordance with the method described under 1 above, the simulation procedure used for the postcalculation was based on two calculation steps. First, the explosion in the borehole and the resulting pressure increase at the borehole boundary were calculated.

In the subsequent calculations to determine the loads in the reinforced concrete structures, the compressive loading (explosion load curves) was applied to the borehole surfaces of the partial model. The calculations were performed using appropriate partial models.

8 COMPARISON OF MEASURED DATA AND CALCULATIONS

In Figure 5 an example of experimental and calculational results for axial and tangential deformation in the model shield is shown. As can be seen, there is good agreement for axial deformation, while circumferential deformation is overestimated by the calculation within a large scatter of results. By adjusting the dynamic parameters of the concrete model including the post-test static tensile and compressive concrete strength the following general results can be deduced:

- The dynamic behavior of the concrete structure is well represented by the calculations both on the time scale and on the scale of the deformation amplitudes.
- The transient data are best represented using a concrete model which preserves at least 70 % of the compressive strength even after two consecutive blasts, while the tensile strength has to be taken low, e.g. 1/5 of the static value for the undamaged concrete.
- These material data derived from the dynamic behavior are in good agreement with the post-test measured concrete strength values.
- Dynamic stiffening factors were applied including data which had been verified in previous tests. A set of calculational coefficients to be used in the material model for reinforced concrete has been derived and is recommended for similar types of high transient loads, e.g. impact and gas explosion.

9 REFERENCES

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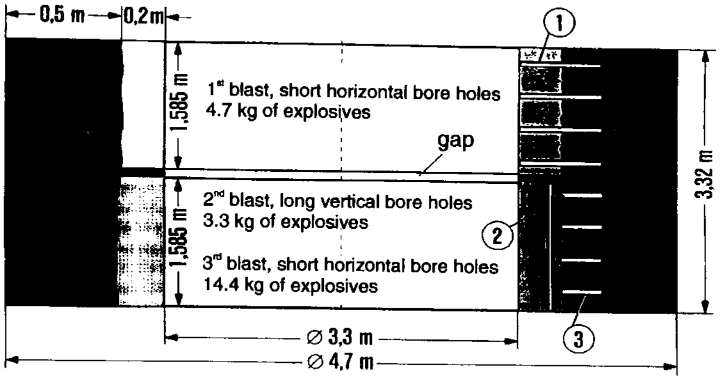

Fig. 1: Concrete ring resembling model biological shield with holes for explosive charging

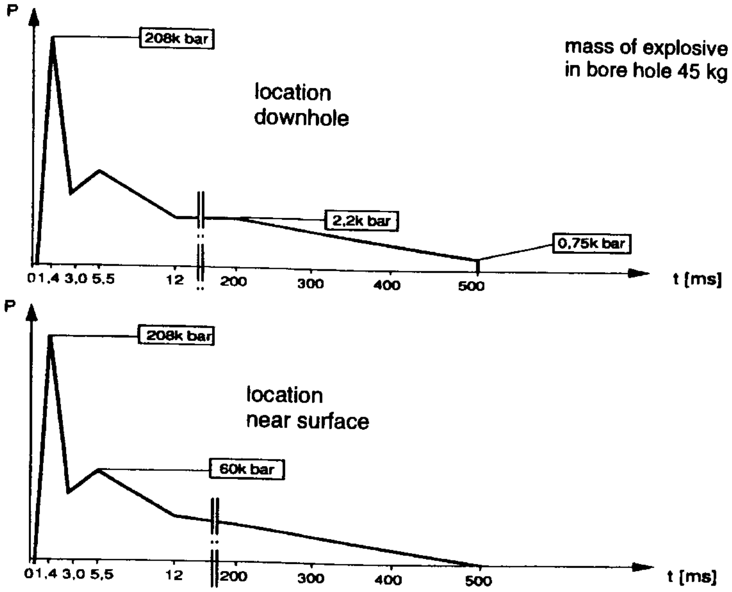

Fig. 2: Bore hole - load functions taken from combination of calculation and previous experiments

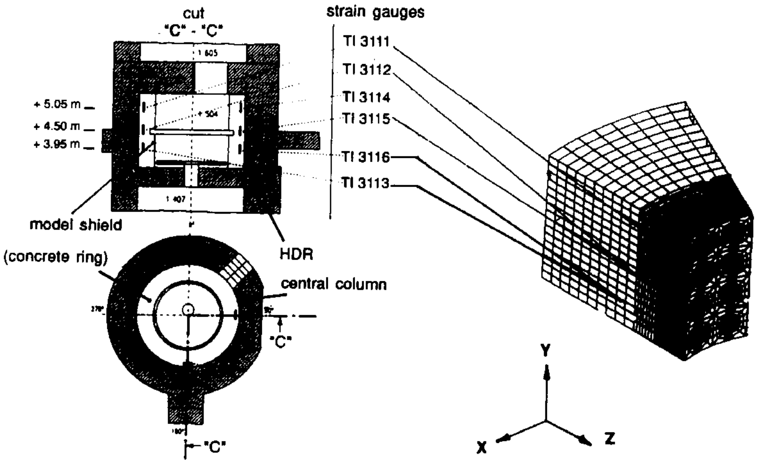

Fig. 3: Concrete ring embedded into HDR-building structure (left) with position of deformation sensors and sectional FE model for calculations (right)

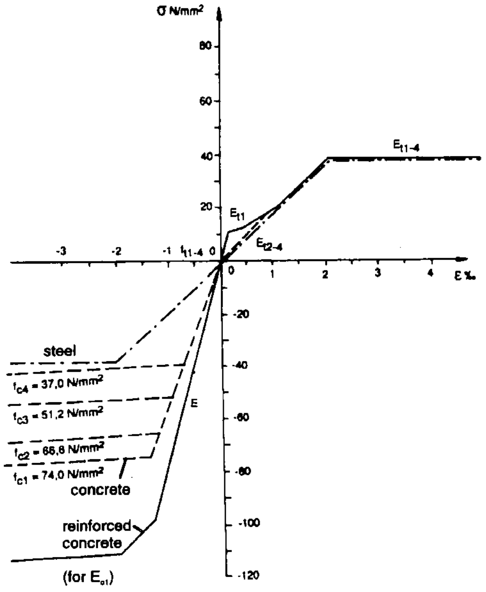

Fig. 4: Stress-strain relations for reinforced concrete

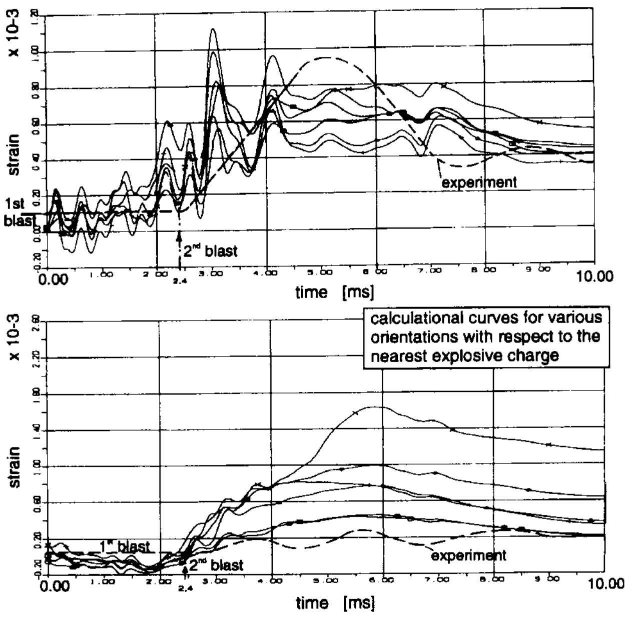

Fig. 5: Axial (top) and tangential (bottom) deformation as a consequence of consecutive explosive loadings: comparison of experiment and calculations assuming unaffected static compressive strength