A Subsequent Containment Examination for Aircraft Impact

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ABSTRACT

For the AVR research facility - a 15 MWe high temperature power unit - operation conditions should be modified. Licensed in the early 60s a re-evaluation against aircraft impact was also required. Since design against this load case had not been performed according to then demands a thorough, high-sophisticated FE analysis was performed by means of two different cylindrical models (with 2990 and 7028 DOF). Conclusively, the results show that the load bearing capacity of the wall middle region could be considered yet possibly tolerable on condition that a reduced load-time-function might be permitted. The extremely time-consuming analyses have been run on a CRAY-1M.

According to the German guidelines for PWRs (1983) aircraft impact is not regarded a DBA due to the low risk to be assumed. Nevertheless the Federal Minister for Environment, Protection of Nature and Nuclear Safety (BMU) requires the design against aircraft impact even when the licensed conditions shall be modified only.

The AVR facility - a high temperature (gas-cooled) research reactor of 15 MWe power - was planned in 1959 and put in operation in 1966. The AVR system is enclosed by a steel containment and its outer biological concrete cylinder which has an outer diameter of 21 m and a wall thickness of 1.50 m with inner and outer bending reinforcement only; due to then demands a shear reinforcement was not required. Therefore, when planning to modify the AVR reactor it was necessary to also analyse its safety potential against aircraft impact.

Since the outer reinforced cylinder is closed through a light steel dome construction the containment re-evaluation can only be realized up to the upper edge of the concrete wall. Consequently, the analyses are carried out for an 'open' cylinder (s. fig. 1).

At first, the most critical load position shall be determined by means of stress influence lines. This is realized using the ASHSD2 code which is a linear program for axisymmetric VOLUME elements with simultaneous application of Fourier series in hoop direction

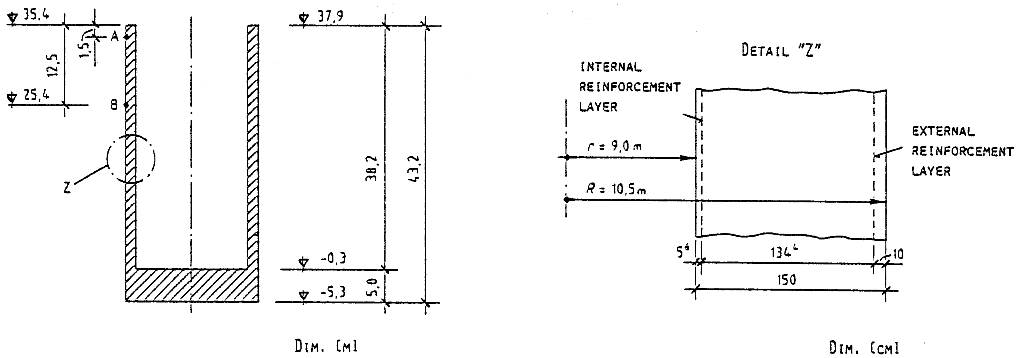


Fig. 1 System and Cross-Section

for arbitrary loading. Due to different stiffness distributions this pre-calculation does not result in one definite load positioning so that for the further analyses is determined:

- Point A at level + 36.4 m for the upper edge
- Point B at level + 25.4 m for the middle area.

For the performance of the 'accurate' study the ADINA code is applied. Usually, the modeling for aircraft analyses is restricted to the closer impact area. However, in order to exclude discussions on realistic boundary conditions the modeling is realized for the complete concrete cylinder (s. fig. 1). Soil-structure-interaction is also taken into consideration determining lumped parameter after Newmark-Rosenblueth. Structural damping is regarded according to the Rayleigh definition. For the reinforcement layers a bilinear material law is assumed, i. e. without isotropic hardening (s. fig. 2), and, in addition, the Drucker-Prager relation defines the concrete material behaviour with or without yielding on cap (s. fig. 3).

According to the RSK-guidelines the load-function (s. fig. 4) is assumed for a defined impact area of 7 m^2 (i. e. a diameter of 3.0 m), however, two different impact angles (measured against the horizontal) are selected

- 0^o with a very low probability of occurrence
- 40^o with a relatively higher probability of occurrence.

The complete structure is modeled through 16 node VOLUME elements representing the concrete cylinder and, in addition, TRUSS elements model the existing reinforcement layers in the impact area. In order to exclude system inaccuracies two models different in mesh-size are implemented

Fig. 2

Material Law : Steel

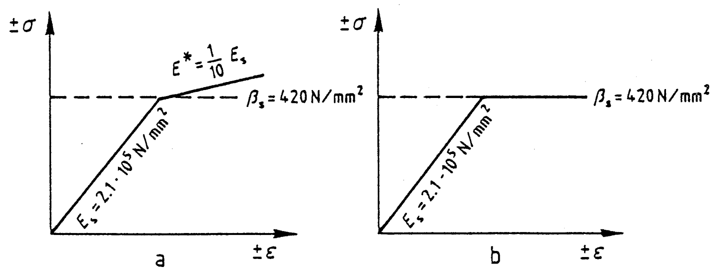
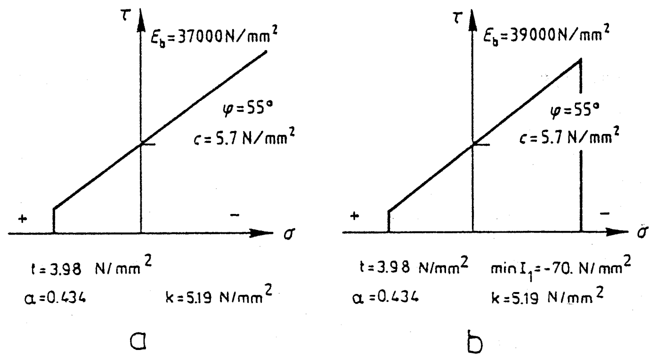


Fig. 3

Material Law : Concrete



- model I being a relatively narrow 3 layers mesh with distinction in model IA and IB for the load application points A and B, respectively
- model II being a narrow 6 layers mesh for the load application point B which is implemented for final structural evaluation.

With regard to numerical accuracy the analyses once again are subdivided into

- nonlinearity in material without iteration
- nonlinearity in material with iteration
- nonlinearity in material and geometry without iteration
- nonlinearity in material and geometry with iteration

The time-step of $\Delta t = 0.00005$ s proves to be satisfactory for model I with 2990 DOF, while $\Delta t = 0.00001$ s is required for model II with 7028 DOF. Model I results obtained from the a.-m. alternatives are found close together which is valid for the computed stresses of the concrete elements and for the strains of steel elements as well.

When evaluating model's I results under horizontal impact (0° angle) non-permissibly high compressive stresses are detected while - for the point B area - similar strain values are found for model I and II which are within the limits given in /2/; on the other hand the 6 layers model shows 20 % higher (unpermissible) compressive stresses than those in model I. Consequently, for the edge area (point A) as well as for the middle area (point B) the structural capacity will be exceeded under the assumptions explained above;

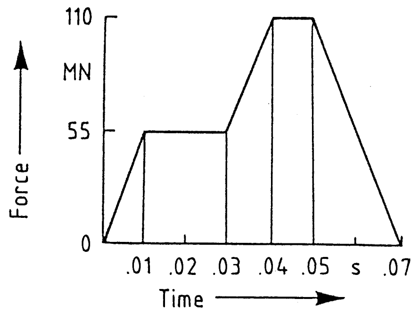


Fig. 4

Load-Time-Function

this counts for the principal tensile stresses as well as for the compressive stresses detected.

Regarding that, firstly from the operational aspect, the AVR reactor is a research facility of small power and, secondly from the structural design aspect, that the check can only be reasonably realized for the open concrete cylinder modified load assumptions might be admissible. In /5/ further details are given with respect to aircraft crash. Hereby, the frequency distribution as a function of the impact angle (against the horizontal) is of most interest. Thus, the 40^o angle is found to be the 50 % rate of occurrence which means a factorization of the load-time-function given in fig. 4 to 0.766.

With respect to a.-m. results the further analyses are performed for point B only; i. e. the impact against the upper edge of the cylinder is neglected. According to fig. 2 and 3 a sensitivity material assumption analysis is carried out. The comparison of model IB.5 and IB.6 results shows similar structural behaviour for strain und stress values as well (s. table 1). Hereby, the maximum compressive stress is remarkably less than the defined concrete ultimate capacity. When comparing model I and II calculated compressive and tensile stresses do not exceed given limits in /2/. Compressive strains - yet linear - are more or less identic in both models, while model I tensile strains are somewhat higher, yet about 5 o/oo. --- When judging the concrete stress capacity the (at least) two-dimensional stress condition (s. fig. 5) permits an increase of the one-dimensional stress limit. The extrapolated maximum compressive stress at the concrete outer surface leads to (tolerable) - 55 N/mm^2. However, the judgement of the numerical model should also not neglect the existing residual tensile stresses.

In addition, also those parameters should be regarded which cannot be completely represented through the (yet high-sophisticated) numerical model. TRUSS steel elements are fixed to the concrete elements at their adjacent nodal points, whereas the reinforcement layers are both continuously bonded to the surrounding concrete and partially overlapped so that within the overlapping joints the steel tensile forces must be transferred through shear bond.

Furthermore, slippage and/or reinforcement stiffness, particularly within the overlapping area, should influence the structural behaviour disadvantageously. In addition, since a shear reinforcement is missing a realistic shear load transfer can only reasonably be judged if the concrete is found in good condition and not pre-defected by cracks.

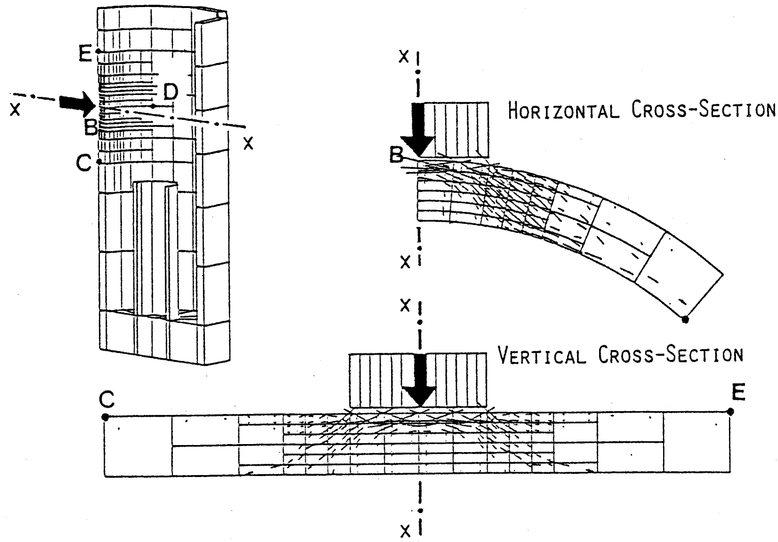


Fig. 5 Trajectories of Compressive Stresses at t = 0.04 s

MODEL	NO. OF LAYERS	DOF	ΔT (s)	ANALYSIS	STEEL	CON-CRETE	LOAD	CPU TIME (s)	MAX σ (MN/M^2)	MIN σ (MN/M^2)	MAX ε %	MAX ε_{PL} %
IB.1	3	2990	5.10^{-5}	M NL O IT				< 6000	7.1	- 71.9	0.80	0.54
IB.2	"	"	"	M NL M IT	"	"	"	"	7.6	- 72.3	0.86	0.59
IB.3	"	"	"	M+G NL O IT	"	"	"	"	7.1	- 72.6	0.83	0.57
IB.4	"	"	"	M+G NL M IT	"	"	"	6381	7.2	- 73.0	0.89	0.62
IB.5	"	"	"	"	"	"		6420	6.1	- 44.5	0.50	0.28
IB.6	"	"	"	"			"	"	6.1	- 44.7	0.54	0.34
IIB.4	6	7028	1.10^{-5}	M+G NL M IT				58400	7.2	- 98.8	0.61	0.37
IIB.6	"	..	"	"				47700	6.7	- 48.2	0.35	0.15

M = MATERIAL
G = GEOMETRY
IT = ITERATION

NL = NONLINEAR
O = WITHOUT
M = WITH

Table 1 Study Overview and Principal Results

CONCLUSION

Results of phase 1 analyses assuming the full load-time-function show:

- For the upper edge (point A) protection against penetration must be excluded
- For the middle area (point B) results seem also tend to exceed the structural ultimate capacity.

In phase 2 analyses are only performed for point B with an 40^{0} angle (against the horizontal) assumed. Valuating all modeling as well as physical conditions the structural capacity of the open cylinder might just lead to protection against penetration. However, this statement can only be given for a concrete matrix in good condition and not pre-defected by cracks.
Results are completed in table 1. The extremely time-consuming analyses have been run on a CRAY-1M.

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