Design Study of a French Nuclear Plant under Aircraft Impact according to German Guidelines

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ABSTRACT

Subject of the paper is the presentation of an aircraft protection for the reactor building and the electrical building of the French nuclear plant P'4 or N4 against the aircraft impact load conditions according to German guidelines. Furthermore, floor response spectra in the interior of the two buildings are evaluated for the induced vibrations resistant design of components. The presented solution leads to acceptable values of either necessary bending and stirrup reinforcements and of the level of equipment accelerations for the reactor building as well as for the electrical building.

1 INTRODUCTION

The containments for pressurized water reactors of the type P'4 or N4 of French nuclear plants are made up of two distinct containments: an internal containment designed to avoid radioactive leaks, and an external one designed to protect the reactor against external hazard, c.f. Barbe and Costaz (1991). The internal containment, in prestressed concrete is designed for the internal pressure that would occur in the event of an accident and the external containment, in reinforced concrete, is designed for the impact of an aircraft.

The reference aircraft, taken into account for the design of the external containment, is the Lear Jet crashing at a speed of 100 m/s.

Electricité de France asked the consultants Stangenberg, Schnellenbach und Partner to design, following German regulations, an external containment such that it could be used for the P'4 - N'4 type reactors and also a rectangular building surrounding the electrical building.

The second part of the study consists of dynamic elastoplastic finite element analysis modelling the complete zones of impact.

The third part allowed the estimation of the effects of vibration induced by the impact of the aircraft on different points on the structures - based on different soil types.

2 FRENCH PRACTICE

Dimensions of the actual building: The external containment P'4 / N4 has a shell thickness varying from 0,55 m for the cylindrical part to 0,40 m for the dome, the internal containment having a thickness varying from 1,20 m to 0,82 m (See Fig. 1).

Two reference aircrafts are considered for the design: the Lear Jet 23 and the Cessna 210, crashing at a speed of 100 m/s.

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The type of impact of the Lear Jet is that of a soft shock creating a force of 12 MN (See Fig. 2), the Cessna design being more of a hard shock (taking into account a minimal thickness of the protecting structure).

Concerning the external containment an elastic design is done although, in the event of accidents with a low probability of occurring, French regulations authorise an elastoplastic behaviour of the resisting structure but actually limits the admissible deformations to 0,8 % elongation of the steel and a 0,35 % shortening of the concrete.

3 GERMAN PRACTICE

In the case of non-reduced impact of an aircraft vertically on a wall, the basis to be taken is the load-time function according to Fig. 3, derived by assumption of a rigid wall.

A circular impact area of 7 m^2 according to an equivalent diameter of 3,0 m of the deformed aircraft is to be assumed in the case of an aircraft and 1,5 m^2 in the case of a wreck (= engine).

Moreover the following characteristic data can be assumed prior to first impact (undeformed aircraft or engine, respectively): Aircraft: mass 20 Mg, speed 215 m/s, diameter (circular cross section 2,5 m).

The strain limit values of concrete and reinforcing steel should not exceed the following values in the case of structural elements subjected to bending: concrete $\varepsilon_b \leq -0{,}5$ %, steel: $\varepsilon_s \leq 2{,}5$ %.

4 PROPOSED AIRCRAFT IMPACT PROTECTION OF REACTOR AND ELECTRICAL BUILDING

The reactor building, electrical building and an additional aircraft protective shield of the electrical building are built on a common continuous foundation slab. The roof slab and the walls of the aircraft protective shield are connected to the external shell of the reactor building by means of a monolithic in-situ structure. The wall thicknesses of the external reactor building shell and of the protective shield are 1.3 m and 1.5 m, respectively. The electrical building is based on the common foundation slab and separated from the other two buildings by a joint. Figure 4 shows a plan view of the reactor building, electrical building and protective shield.

Three impact points have been considered: (1) Vertical aircraft impact, (2) horizontal aircraft impact, (3) oblique aircraft impact.

For each of the three impact points, a different finite element model has been generated, due to the necessity of a very refined mesh discretization in the impact area. The concrete is modelled by 3-d nonlinear and linear volume elements, while reinforcing steel is modelled by truss elements. For both concrete and reinforcement, nonlinear stress-strain laws are taken into account. The computations have been carried out using the Finite-Element method described by Bathe (1976).

The input for the nonlinear 3-d computations of the external reinforced concrete shell are:

- shell-thickness : $d = 1{,}30$ m
- concrete : f_{c28}: 40 MPa = B 45
  $\beta_{WN} = 45$ MN/m^2
- reinforcement : S 400
- bending reinforcement each face, each way
- shear reinforcement Z-stirrups

dome shell : $a_{s1} / a_{s2} = 75{,}0 / 75{,}0$ cm^2/m
$a_{s\tau} = 75{,}0$ cm^2/m^2
cylindrical shell : $a_{s1} / a_{s2} = 80{,}0 / 80{,}0$ cm^2/m
$a_{s\tau} = 75{,}0$ cm^2/m^2

Three-dimensional elements (concrete)

A special concrete material model to describe the nonlinear stress-strain relation, stress induced orthotropy, tensile failure, compressing crushing and post failure behaviour of concrete including strain softening is used. It reproduces the important experimentally observed stiffness and strength characteristics. The model is used for three-dimensional elements in the impact area.

For the concrete model there are three basic features that are used to describe the material behaviour, namely, (i) a nonlinear stress-strain relation to allow for the weakening of the material under increasing compressive stresses, (ii) a failure envelope that defines failure in tension and crushing in compression, and (iii) a strategy to model the post-cracking and crushing behaviour of the material.

Truss elements (reinforcing steel)

The truss elements are used to model the reinforcing steel of the structure. They are assumed to have constant areas. The stress-strain law, used in the computations, is elastic-plastic with kinematic hardening conditions.

Step-by-step solution

Once the required element matrices have been calculated, the structure matrices are obtained using standard assemblage procedures. In nonlinear dynamic analysis and implicit time integration the modified Newton iteration method is used to solve the equilibrium equations, with the integration parameters $\delta = 0{,}5$ and $\alpha = 0{,}25$. The used time increment is $\Delta t = 0{,}5$ ms.

Results

Figure 5 gives plots of the deformed shape of the models for horizontal and oblique impact, respectively, at the time steps with maximum displacement (6,5 cm for horizontal and 1,8 cm for oblique impact). The maximum strain of bending reinforcement was 0,6 %, which is much lower than the allowed value, c.f. chapter 3. However, the maximum shortening of concrete reached $\varepsilon = -0{,}4\%$, which is in the range of the allowed value.

Table 1Max. strains and deformations of the r/c shell

	vertical	horizontal	oblique
max. displacement	7.7 cm	6.5 cm	1.8 cm
time	58 ms	54 ms	48 ms
max. strain (bending)	6.2 ‰	4.8 ‰	1.3 ‰
time	53 ms	52 ms	44 ms
min. strain (bending)	-4.1 ‰	-3.7 ‰	-1.4 ‰
time	52 ms	52 ms	42 ms
max. strain (shear)	1.3 ‰	0,8 ‰	0,5 ‰
time	50 ms	50 ms	48 ms

5 INDUCED VIBRATIONS DUE TO AIRCRAFT IMPACT

For the dynamic computations, the electrical- and reactor building, the aircraft protective shield and the common foundation slab are idealized by a 3-dimensional finite-element model, see Figure 6.

Three different soil moduli in the range from soft soil to hard soil are taken into account. The corresponding soil properties (dynamic shear modulus of soil G, Poisson's ratio ν) are: G = 100 MPa and ν = 0,47 (soft soil), G = 700 MPa and ν = 0,43 (medium soil) G = 2.500 MPa and ν = 0,40 (hard soil).

The capability of the finite-element model to transmit loads reaches from 0 to about 30 Hz. Examples of modal shapes are given in Fig.7.

In Figure 8, examples of resulting floor response spectra for different building points are given.

REFERENCES

Barbe, B. and Costaz, J.L. (1991). Design and Behaviour of French Containments, Nuclear Engineering and Design (12/1991-5773)

Bathe, K.-J. (1976). Static and Dynamic Geometric and Material Nonlinear Analysis using ADINA, Report 82 448-2, Massachusetts Institute of Technology, Cambridge.

Bathe, K.-J., Wilson, E.L. (1976). Numerical Methods in Finite Element Analysis Prentice Hall, Englewood Cliffs, New Jersey.

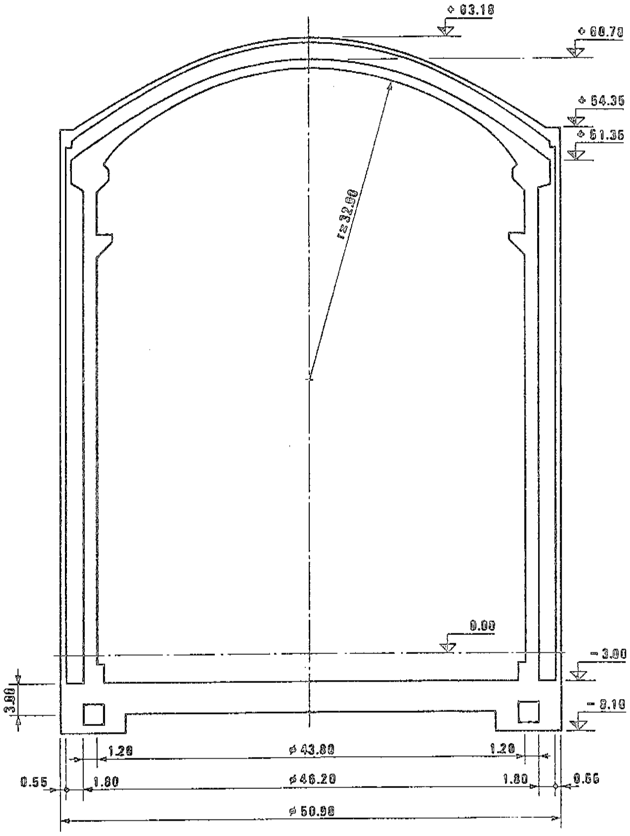


Fig. 1 Section of Reactor Building P'4

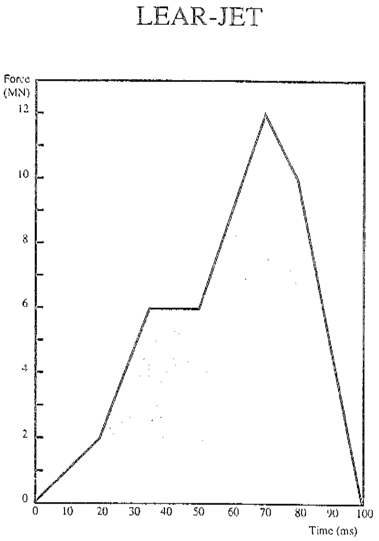
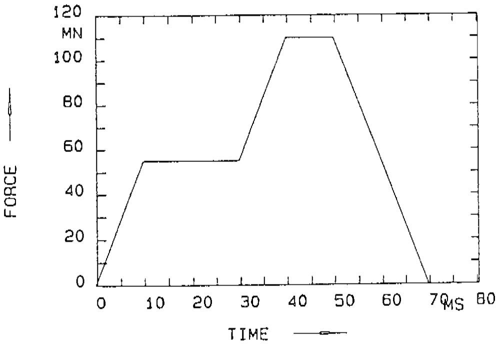


Fig. 2 Load-Time Function of Lear Jet



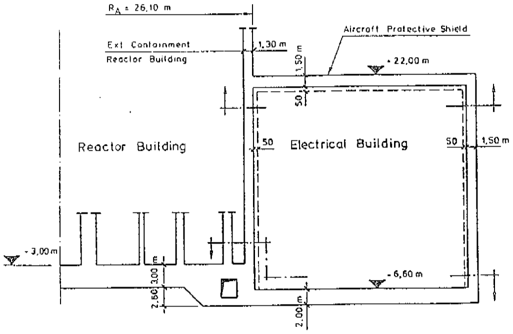


Fig. 3 Load-Time Function acc. to German Guidelines

Fig. 4 Section of Reactor and Electrical Building

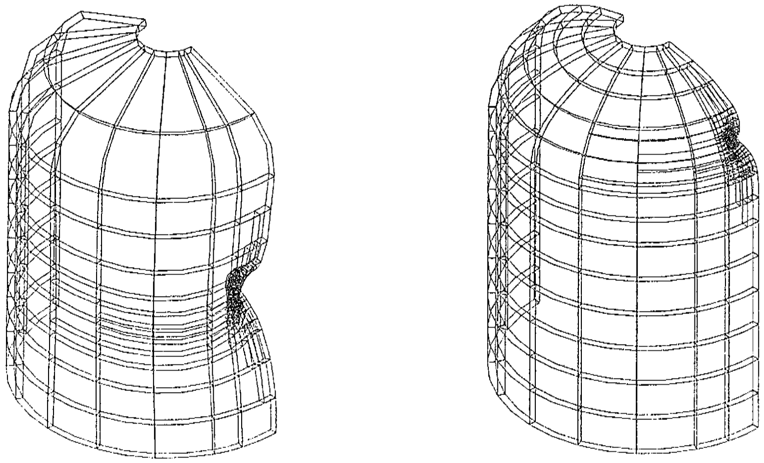


Fig. 5 Deformed shapes in case of horizontal and oblique impacts (nonlinear results)

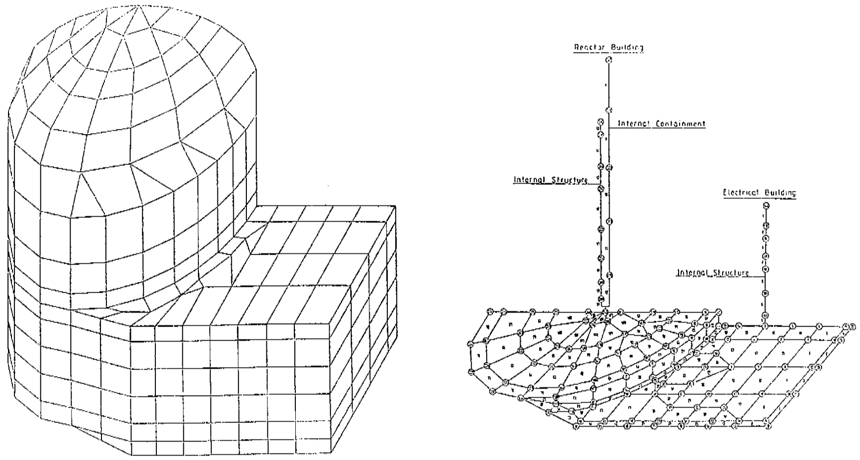


Fig. 6 Finite-Element Model for Spectra Evaluation

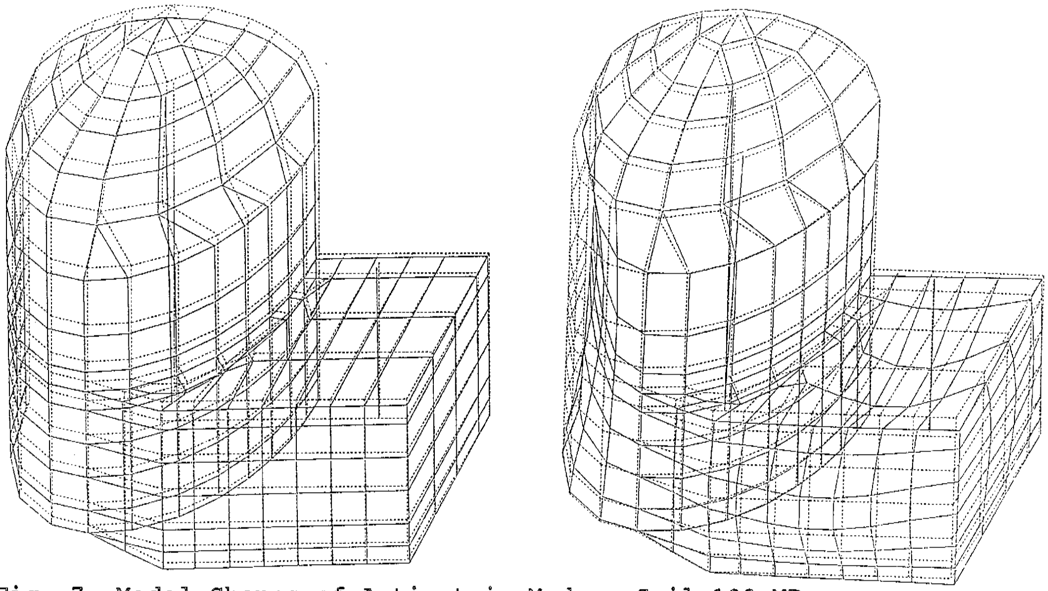
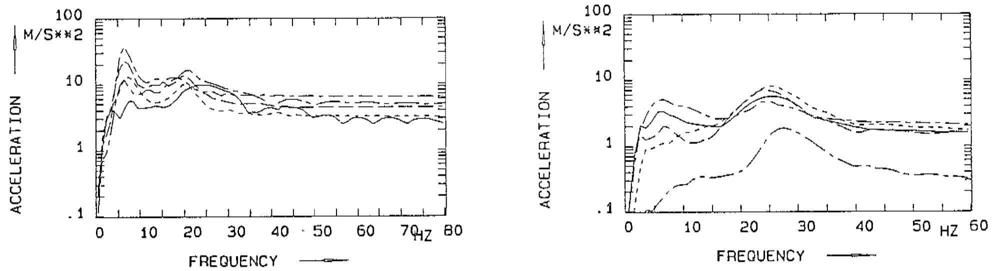


Fig. 7 Modal Shapes of Antimetric Modes, Soil 100 MPa, f_1 = 1.14 Hz (left), f_6 = 5.97 Hz (right)

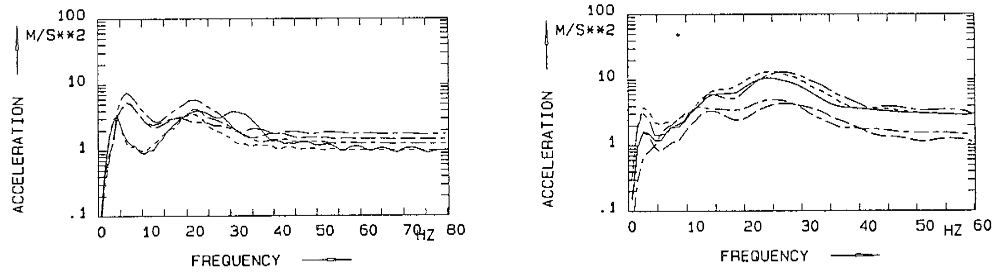


REACTOR INT. CONTAINMENT +27.0 M HOR. SOIL 700 MPA

——— IMPACT 2 ----- IMPACT 3
—·— IMPACT 4 ——— IMPACT 4 A
—·–· IMPACT 5

ELECTRICAL BUILDING +19.30 M HOR-X. SOIL 100 MPA

——— IMPACT 1 ----- IMPACT 2
—·— IMPACT 3 ——— IMPACT 4
—·–· IMPACT 5



REACTOR INTERNAL STRUCT +22.4 M HOR. SOIL 700 MPA

——— IMPACT 2 ----- IMPACT 3
—·— IMPACT 4 ——— IMPACT 4 A
—·–· IMPACT 5

ELECTRICAL BUILDING +19.30 M HOR-Y. SOIL 100 MPA

——— IMPACT 1 ----- IMPACT 2
—·— IMPACT 3 ——— IMPACT 4
—·–· IMPACT 5

Fig. 8 Examples of Floor Response Spectra