The Local Deformations Caused by an Aircraft Impact on a Containment Building

J. Puttonen

Imatran Voima Company, Civil Engineering Department,
P.O. Box 138, SF-00101 Helsinki 10, Finland

Summary

This study was carried out to find a sufficient wall thickness for a containment building against an aircraft impact. The used load-time function simulates the impact of a military aircraft with the weight of 20 tons and velocity of 200 m/sec. The outside radius of the dome has been 24 m. Because of the highly nonlinear nature of this analysis geometric and material nonlinearities have been considered. A suitable computer code to solve this kind of problems is PISCES-2DELK developed by Physics International Company. Description of material models was made in the spirit of the Finnish reinforced concrete code. The reinforcement was described by von Mises model. However, for the concrete a one dimensional von Mises type material model represented in the code was found to be unrealistic. The conclusion was that the cohesion and internal friction of concrete have to be included. So the Mohr-Coulomb model available in PISCES was employed. The advantage of this model is that the cracking is included. On the contrary, there is no limit on the compression side which occured to be very significant disadvantage, since the failure criteria must base on strains of concrete. This failure criteria leads to wall thickness of over 2 m which is considerable more than that obtained by previous PISCES analyses. The maximum allowable strain value for concrete was 0.35 % evaluated by using the Finnish reinforced concrete code. If that value was exceeded in a large region the failure took place. The effect of the magnitude of the reinforcement was also investigated, and found to be nonessential. The main task of the reinforcement is to keep the concrete together, and it can be neglected when the absorbtion of energy is considered. The energy absorbed by the structure is mainly distortion energy from which the energy taken by the concrete is over fifteen times greater than that of the reinforcement. The phenomenon is very local; outside a radious of 3 m from the middle point of an impact deformations are small. If the thickness of a containment building is about 2.1 m the maximum displacement is 0.35 m. In this case damages due to an impact will be easily repaired. However, complete insurance against scabbing is reached only by using an internal liner.

1. Introduction

Analysis of the behaviour of a containment building due to an aircraft impact may be divided into two different parts. In global analyses the overall response of a structure is considered. In this case linear theory of elasticity can usually be applied, since the nonlinear effects of an aircraft impact are very local phenomena which have only a small effect on the total behaviour of the structure /1/. Whereas in the case of local effects our concern is just concentrated in these nonlinear phenomena of geometrical and material behaviour. So it is quite understandable that the ordinary methods of structural mechanics are ineffective to simulate the structure in the vicinity of an impact area. That is why several empirical formulas, as ACE-, NCRD-, BRL- and IRS-formula /2/, have been developed to estimate penetration depth, perforation and scabbing thickness for concrete targets subjected to impact load. These formulas have also been used to determine effects of an aircraft impact in nuclear power plants. Because of the scale difference between the test models on which the empirical formulas based and the nuclear power plants follows that the results of these formulas are unreliable and can be unrealistic in the case of an aircraft impact.

A suitable computer code to analyse the local effects of an aircraft impact is PISCES-2DELK developed by Physics International Company. This is a two-dimensional explicit finite difference programme capable to solve dynamic structural and flow problems. Because of the two-dimensional nature of this code it is supposed that an aircraft will impact to the top of the containment building. In this case an axisymmetric model can be employed.

The aim of this study is to give an estimation for the sufficient thickness for the containment building capable to withstand an aircraft impact. Failure criteria used has been mainly based on strain capacity of concrete.

2. Impact load

The used load-time function simulates the impact of a military aircraft with a weight of 20 tons and velocity of 200 m/sec. It is supposed that the impact of the fighter is directed along the normal of the surface and uniformly distributed to a circular area with a radius of 1.6 m (8 m^2). The time dependence of the impact force has been given in Fig. 1. The load function corresponds to IRS-formula for an aircraft of Phantom RF-4E type/3/ with slight modifications. The load function has been derived assuming that the impact acts against an infinitely rigid wall. So the local plastification and inertia of the concrete are excluded. The load function derived under these assumptions is usually very conservative.

3. Finite difference model of the shell wall

Because of the local nature of this analysis the shell structure around the impact area is included up to the point where the angle between the radius of the shell and the axisymmetric line is 45^0. The outer radius of the shell is 24 m. Thickness of the shell is altered by reducing the inner radius. The reinforcement has been described by uniform steel layers capable to withstand only membrane forces. The layers have been placed at a distance of 10 cm from the surfaces of the shell. The magnitude of the reinforcement has been 200 kg/m^3. A general description of the discretized model has been shown in Fig. 2.

The finite difference mesh has been designed in order to obtain a sufficient description about the changes of displacement and strain fields. The changes due to the impact load are significant only a few meters from the load area. So the mesh is finer in the vicinity of the symmetric line and becomes coarser when the distance from the symmetry line is increasing. Mesh points are defined according to column and row numbers. In this model curved lines are columns and straight lines are rows. Boundary conditions have been as follows: at the fixed edge the both components of velocity are zero and at the symmetry line only the y-component is zero. The external force is the pressure due to an aircraft impact.

4. Material models

The description of steel properties is made according to the reinforced concrete code which means that work-hardening is not included but von Mises yield model is employed. As a yield limit of the steel 460 MN/m^2 has been used. In this figure an addition of 15 % due to the dynamic effect is also included. The values of Young modulus and Poisson ratio were 2.1×10^5 MN/m^2 and 0.30, respectively. Density of the steel has been 8000 kg/m^3.

As known, it is very difficult to find a simple way to describe the properties of the concrete. The most common assumption is to exclude the tensile strenght of the concrete. However, in this particular case that assumption leads to unrealistic results as we noticed in the connection with a test example. From this it follows that the behaviour of the concrete cannot be modelled according to the concrete code but the cohesion and the angle of friction must be included in the material model. In PISCES-2DELK the best available material model for the concrete is a modified Drucker-Prager formulation /4/ presented in the form of:

$$Y = ap + b \qquad (1)$$

where Y is the yield strength, p the pressure, a and b are material constants which are related to the cohesion and the angle of friction. The yield strength Y is a function of the second invariant of the deviatoric stress tensor. In the PISCES code there are two additional parameters associated to

the Mohr-Coulomb material model. One is the maximum yield strength from which the material behaves as a von Mises material, so there is no dilatancy due to yielding. The other is a spall limit on the tensile side. The graphical representation of the used concrete model is shown in Fig. 3.

5. Results

The reinforcement was approximated by continuous steel layers, which means that the plastic capacity of the structure is overestimated and the moment of failure must be concluded by the values of strains. The maximum allowable strain value for the concrete has been estimated by using the Finnish reinforced concrete code and it was 0.35 %. If that value is exceeded in a large region failure will take place. Since the capacity of the steel layers to absorb energy is directly proportional to the volume of the steel and the state of strain it is obvious that with these steel magnitudes and possible strains which are allowed to reinforced concrete the effect of steel can be neglected when the absorbtion of energy is considered. This was also testified by analysing the dome with a constant wall thickness 1.5 m and using two different magnitude of reinforcement, namely 80 kg/m^3 and 200 kg/m^3. The strain histories of these analyses are presented in Tables 1 and 2. In all the analyses the upper steel layer was assumed to be thinner than the lower one to make the structure more ductile under an input load.

The dome was analysed with three different wall thickness: 1.5 m, 1.8 m and 2.1 m. The reinforcement was 200 kg/m^3. In Fig. 4 - 6 the deformed form of the structure and stresses in the concrete region have been shown at the moment of 80 msec. The values of the strains of the steel layers at different time points have been represented in Tables 3 - 4 for the wall thicknesses of 1.8 m and 2.1 m. After the failure point presented in Tables the structure resists loading unrealistically by the membrane forces of the steel layers due to the analysis model. When the wall thickness is 2.1 m the values of the strains are within an allowable range during the whole impact, excluding a few local exceedings. Also the fact that the values of the strains are descending at the moment when the calculation has been interrupted supports the conclusion that the containment building is able to stand an aircraft impact. The maximum displacement is about 0.35 m and compression 0.02 m at the symmetry line. First cracks occured after 50 msec. At 80 msec the concrete has failed both at the bottom and top layers in the vicinity of the impacted area. It is probable that the direction of cracking is radial in inner layers if so the cracked concrete is held together by the reinforcement. Complete insurance against scabbing is reached, however, only by using an internal liner. The obtained wall thickness of 2.1 m agrees well with the results represented by Alderson et.al. /5/ but is slighty more than the value of 1.8 m obtained by Hoek and Ree /1/. In Fig. 7 and 8 the energy distribution associated with the thickness of 2.1 m and the

mean velocity at the symmetry line are shown, respectively.

6. Conclusion

The required wall thickness against an aircraft is about 2.1 m according to our PISCES analyses. In this case the damages due to an impact will be easily repaired, and also scabbing can be completely avoided by an internal liner. The impact will cause a local deformation and outside a radius of 3 m deformations are small independently of the wall thickness. The energy absorbed by the structure is mainly distortion energy, and energy taken by the concrete is over fifteen times greater than that of the steel layers. So the main task of the reinforcement is to keep the concrete together. However, it should be noted that the used load-time function is very coservative, since deformations and inertia of the target are excluded.

References

/1/ Ree, H.v.d., Hoek, M.S.v.d., "Analysis of the Behaviour of a Concrete Structure due to an Airplane Impact and the Effects of the Reinforcement", 5th SMIRT Conference, Report J9/5, Berlin, 1979.

/2/ Structural Analysis and Design of Nuclear Plant Facilities, ASCE,1976.

/3/ Institut für Reaktorsicherheit der TÜV E.V., RSK-Leitlinien für Druckwasserreaktoren, 1. Ausgabe, April, 1974.

/4/ Hoek, M.J., "Modelling of Concrete by a Mohr-Coulomb Model", Physics International Technical note: TN-7802.

/5/ Alderson et.al., "Reinforced Concrete Behaviour due to Missile Impact". 4th SMIRT Conference, Report J7/7, San Francisco, 1977.

Table 1. Thickness 1.5 m, reinforcement 80 kg/m^3. Development of meridional strain in the steel layers [‰].

	row / time ms	row 2		row 3		row 4		row 5		row 6	
		upper layer	lower layer	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer
	19.5	-1.1	0.1	-2.5	-0.3	-1.6	-0.5	-2.2	-0.5	-0.4	-0.8
	24.2	-1.5	-0.2	-3.1	-0.7	-1.2	-0.9	-2.8	-0.9	-0.5	-1.1
	29.1	-1.6	-0.3	-3.5	-0.7	-0.5	-0.9	-2.3	-0.9	-0.6	-1.2
	34	-1.2	0.2	-2.2	-0.1	1.0	-0.2	-1.2	-0.3	-1.0	-0.9
failure point	38.8	-0.2	1.7	0.5	1.7	5.8	1.5	1.6	1.3	1.7	0.1
	48.3	5,2	23.5	12.7	17.8	43.8	5.7	15.2	1.2	10.3	0.8
	52.9	14.2	43.6	33.7	32.5	83	11.6	20.6	1.9	18.0	1.1
	57.5	33.8	71.0	69.3	51.8	135	20.1	22.4	14.0	27.1	1.1
	62.0	60.8	104	113	73.6	193	30.6	22.1	7.2	36.1	1.1
	66.4	91.1	139	155	94.6	248	40.0	21.6	10.0	43.7	0.8
	70.8	123	173	193	113	292	48.5	21.3	13.2	50.0	0.7
	75.2	147	201	201	124	316	54.3	21.4	16.0	54.7	0.8
	78.4	155	215	201	129	315	57.1	20.9	17.8	56.5	0.7

Table 2. Thickness 1.5 m, reinforcement 200 kg/m^3. Development of meridional strain in the steel layers [‰].

	row / time ms	row 2		row 3		row 4		row 5		row 6	
		upper layer	lower layer	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer
	20	-1.0	-0.3	1.2	-0.5	-1.1	-0.6	-1.2	-0.6	-0.7	-0.6
	25	-1.1	-0.4	-1.2	-0.7	-1.0	-0.8	-1.1	-0.8	-0.7	-0.9
	30	-0.8	-0.2	-0.7	-0.4	-0.4	-0.4	-0.5	-0.5	-0.6	-0.7
	35	0.3	0.6	0.8	0.6	1.3	0.6	0.7	0.4	0.2	-0.2
failure	40	1.7	1.7	4.6	1.6	2.6	1.5	2.8	1.4	1.3	0.5
point	45	7.0	5.4	11.0	4.4	2.3	1.3	6.1	1.8	3.1	0.8
	50	14.7	11.0	18.2	8.3	4.6	3.1	10.5	1.7	6.2	1.0
	55	29.1	19.0	30.3	13.1	14.3	5.7	10.8	1.4	8.6	1.5
	60	46.7	28.5	43.2	18.4	23.2	8.8	10.7	2.2	11.0	1.7
	65	57.8	35.3	50.4	22.5	26.6	11.3	10.5	4.3	13.1	1.6
	70	59.0	36.5	50.3	23.2	26.0	12.3	9.3	5.8	13.1	1.7
	75	58.2	36.3	50.0	23.1	25.2	12.3	8.7	5.8	12.1	1.5
	80	58.2	35.8	50.1	22.7	25.8	11.9	8.9	5.5	12.4	1.3

Table 3. Thickness 1.8 m, reinforcement 200 kg/m^3. Development of meridional strain in the steel layers [‰] .

	row / time ms	row 2		row 3		row 4		row 5		row 6	
		upper layer	lower layer	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer
	20	-0.4	0.1	-0.5	-0.0	-0.5	-0.0	-0.6	-0.1	-0.2	-0.2
	25	-0.5	0.0	-0.5	-0.1	-0.5	-0.2	-0.6	-0.2	-0.2	-0.2
	30	-0.6	-0.0	-0.6	-0.1	-0.5	-0.2	-0.6	-0.2	-0.3	-0.3
	35	-0.8	-0.2	-0.8	-0.3	-0.7	-0.4	-0.8	-0.4	-0.4	-0.4
	40	-1.2	-0.5	-1.0	-0.6	-0.8	-0.7	-1.0	-0.7	-0.7	-0.7
	45	-1.0	-0.6	-0.8	-0.7	-0.5	-0.7	-0.8	-0.8	-0.7	-0.9
	50	0.6	0.3	1.1	0.3	1.68	-0.4	1.1	0.2	0.4	-0.4
failure	55	3.9	2.1	8.6	2.1	2.5	1.5	4.7	1.8	2.1	0.6
point	60	10.2	5.8	15.2	4.2	2.2	1.3	9.2	2.0	4.4	1.1
	65	14.1	6.3	17.3	4.8	2.9	1.6	-7.5	2.1	5.9	1.2
	70	13.9	6.1	17.1	4.7	2.5	1.5	12.4	1.9	6.2	1.3
	75	12.7	6.0	15.6	4.5	0.8	1.5	10.7	1.7	5.3	1.3
	80	12.6	6.0	15.7	4.5	0.8	1.5	10.7	1.7	5.4	1.4

Table 4. Thickness 2.1 m, reinforcement 200 kg/m^3. Development of meridional strain in the steel layers [‰].

row / time ms	row 2		row 3		row 4		row 5		row 6	
	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer	upper layer	lower layer
20	-0.2	0.1	-0.2	0.1	-0.1	0.1	-0.1	-0.0	-0.0	-0.0
25	-0.2	0.2	-0.2	0.1	-0.1	0.1	-0.1	0.0	-0.0	-0.0
30	-0.3	0.2	-0.3	0.1	-0.1	0.1	-0.1	0.0	0.0	-0.1
35	-0.4	0.2	-0.4	0.1	-0.3	-0.0	-0.3	-0.1	-0.1	-0.1
40	-0.8	-0.0	-0.7	-0.0	-0.5	-0.3	-0.7	-0.3	-0.4	-0.3
45	-1.2	-0.4	-1.0	-0.5	-0.8	-0.6	-1.1	-0.6	-0.7	-0.6
50	-1.2	-0.8	-0.9	-0.9	-0.7	-1.0	-1.0	-1.0	-0.8	-1.0
55	-0.3	-0.6	-0.0	-0.7	0.4	-0.6	0.1	-0.7	-0.2	-0.9
60	1.4	0.6	2.6	0.6	2.1	0.7	2.1	0.6	1.0	-0.1
65	4.0	1.4	6.9	1.4	2.0	1.5	3.9	1.6	1.8	0.6
70	4.5	1.5	7.5	1.4	1.9	1.4	4.6	1.8	2.1	0.7
75	3.8	1.2	6.5	1.2	0.7	1.2	3.7	1.4	1.4	0.4
80	3.1	1.1	6.0	1.1	0.1	1.1	3.0	1.4	1.1	0.4

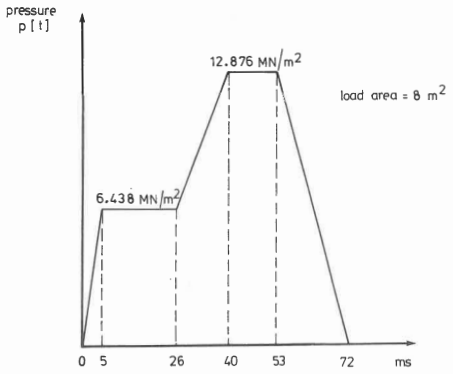

Fig. 1. Load-time history of an aircraft impact.

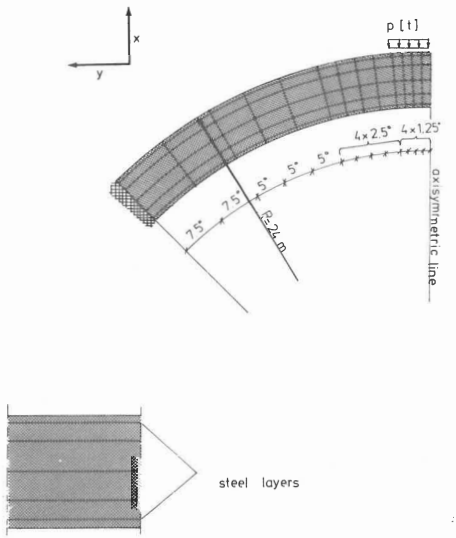

Fig. 2. General description of the discretized model.

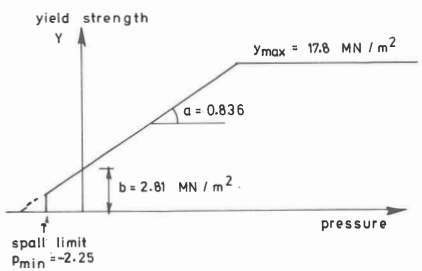

Fig. 3. Material model of concrete.

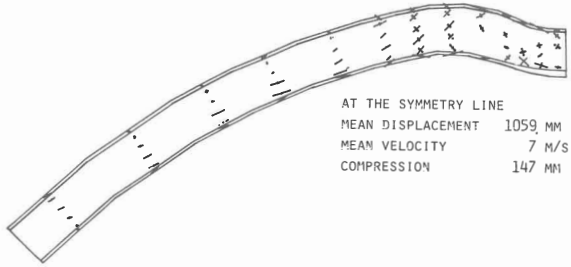

Fig. 4. Thickness of the shell 1.5 m, time 80 msec.

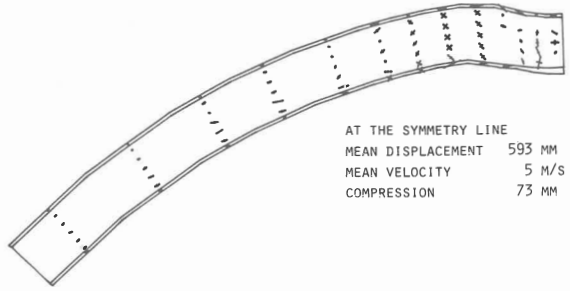

Fig. 5. Thickness of the shell 1.8 m, time 80 msec.

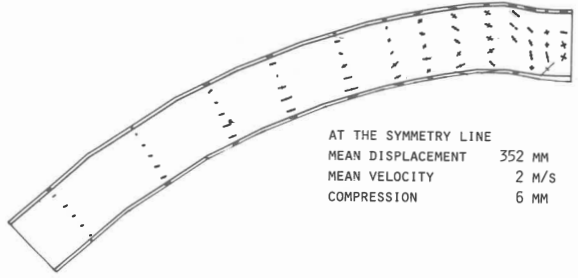

Fig. 6. Thickness of the shell 2.1 m, time 80 msec.

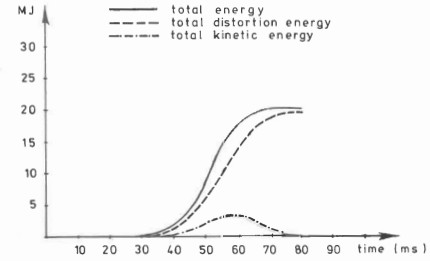

Fig. 7. Energy distribution associated with the thickness of 2.1 m.

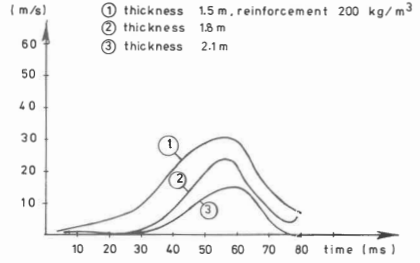

Fig. 8. Mean velocity at the symmetry line.