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Design of the roof slab of a radioactive waste building with special requirements for aircraft impact

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ABSTRACT: The roof slab of the new repository building for medium radioactive waste should not collapse under aircraft impact. The resistance of the slab could be determined by using the charts for an elastoplastic single degree of freedom system (SDOF system). The flexural resistance of the slab was determined according yield-line theory. It shows that the slab can safely withstand the impact load. The displacement and rotational ductility of the slab could be verified according to previously published research work.

1. INTRODUCTION

Within the framework of the ZWILAG Project a building complex is to be constructed in Switzerland for the intermediate storage and conditioning of radioactive waste. The repository building M in this complex serves as an intermediate storage for medium radioactive waste. According to the safety report, aircraft impact is not a design condition. However, due to the thickness of the concrete slab (1.50 m), in considering potential damage it was assumed that under aircraft impact the roof will not collapse. According to the Swiss HSK guideline R-102 complete protection against the penetration of heavy, compact aircraft parts is guaranteed [1]. Based on the results of the investigation presented in this paper it is shown that the roof slab satisfactorily fulfils the assumptions regarding behaviour under aircraft impact.

2. ROOF CONSTRUCTION

The roof slab with spans of 53.15 m and 33.20 m and concrete of class B 45/35 is reinforced with steel S 500. The bottom reinforcement in the transverse direction at mid-span is ∅ 34/ e =15 cm, in the longitudinal direction it is ∅30/e=15 cm, in both directions the top reinforcement is ∅ 26/e = 15 cm. At the supports the amount of top steel present in the transverse direction is 2 x ∅ 30/e = 15 cm and in the longitudinal direction 2 x ∅ 26/e = 15 cm.

3. LOADING ASSUMPTIONS

The load-time diagram for aircraft impact is given in the HSK guideline (Fig. 1). This diagram is based on the calculation of impact normal to a rigid wall.

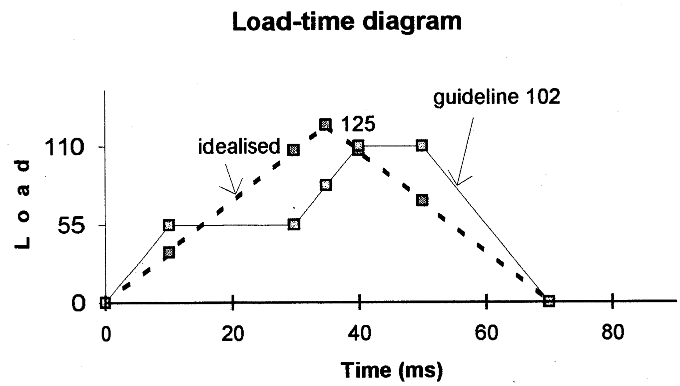

Fig. 1: Load-time diagram from [1]

4. ANALYSES

4.1 Statical analysis

An FE model was developed for the statical analysis of the slab using the program ANSYS [2] for permanent loading. The maximum moments at mid-span are Mx(max) = 1.803 MNm/m, My(max) = 0.762 MNm/m and at the supports Mx(min) = -3.447 MNm/m, My(min) = -2.479 MNm/m.

4.2 Determination of the ultimate load bearing capacity of the slab

With the maximum steel content of 6.72‰. plastic moments occur due to yielding of reinforcement. According to [4] under aircraft impact at high strain rates the yield limit and tensile strength increase 12 - 13%. For the determination of the moments of resistance at yield a steel strain of 2.2‰ was assumed and for the stress 550 N/mm ^{2} with a 10% increase of the yield limit. Thus from equilibrium conditions for the internal forces and moments a concrete strain of 0.84‰ results, with the stress-strain curve for concrete from [5]. The HSK guideline permits a yield strain of 0.5% for concrete and 1% for steel. For this case a yield stress increase of 10% on the average of 605 N/ mm ^{2} is taken. The moments of resistance are summarised for the X-direction and bottom reinforcement in Table 1.

The moments at mid-span due to permanent loads lie below the yield moments. For the permanent loads, before impact, the elastic strains are about 1‰. They remain elastic up to 2.2‰. For 1% maximum plastic strain the ductility reaches the value 10 for impact.

Table 1: The moments of resistance

Direction	Position of reinforce-ment	Eff. Depth in m	Strains in ‰		Stresses in N/mm²		Moments of resistance in MNm/m
			Concrete	Steel	Concrete	Steel	
X	bottom	1.45	0.84	2.20	15.3	550	4.344
			1.98	10.00	23.0	605	4.988

4.3 Determination of the equivalent quasi-static load

For the determination of the equivalent quasi-static load the response of an elastoplastic SDOF system for the slab was assumed. Its fundamental frequency, determined from a modal analysis using ANSYS, was 5.5 Hz [2], whereby an idealisied impact load diagram of triangular form as shown in Fig. 1 was assumed. The maximum response of the elastoplastic SDOF system was determined with the help of the diagrams from [6] with the following calculation parameters: t_D: impulse period = 70 ms, T: period of the elastoplastic SDOF system = 182 ms, ym: total displacement, yel: elastic deformation, μ: ductility = ym/yel = 10. With $t_{D/T}$ = 0.4 and μ = 10 the value Rm/F_1 = 0.27 results. Thereby 27% of the impact load of 125 MN (i.e. 33.8 MN) acts as elastic restoring force on the slab.

4.4 Determination of the load capacity of the slab using yield-line theory

Before impact the slab carries permanent loads. If the concrete in the tensile zone is cracked, the stresses in the reinforcement amount to about one-half the yield limit. The residual resistances can be determined by subtracting the moments due to permanent loads from the plastic moment. Roughly the same structural resistances are present in the slab, except at the supports. In determining the load bearing capacities the slab is assummed to be isotropic with a resistance of m = 3.000 MNm/m and m' = -3.000 MNm/m.The model shown in Fig. 2 can be used to determine the load capacity by yield-line theory.

The point of impact on the roof slab is arbitrary with a circular area of 7 m^2. According to [7] and [8] the yield-line under a concentrated load may form as shown in Fig. 3. The plastic moments for a distributed area may be found using the formula below:

$$m + m' = (1 - \frac{2\rho}{3r})\frac{P}{2\pi} \qquad (1)$$

In this formula the symbols denote: m: positive plastic moment, m': negative plastic moment, P: concentrated load, ρ: radius of distribution area, r: radius of circular yield-line. For the residual load capacities for m and m' a concentrated load P = 41.6 MN results. This load is greater than the quasi-static equivalent load of 33.8 MN. This means that after impact the yield-line will not be fully developed. There is a safety factor of 1.23 against collapse, which is higher than the required value of 1.15 in the HSK guideline, allowed with the use of plastic methods of analysis.

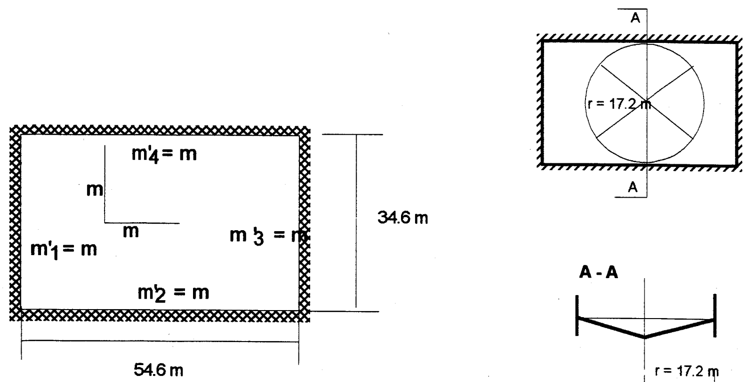

Fig. 2: Computational model for the slab showing yield-lines under a concentrated load

5. VERIFICATIONS

Yield-line analysis requires that the load bearing capacity of the slab is given when the reinforcement completely yields. No brittle failure in a concrete compression zone or due to shear action is permitted. The corresponding verifications are explained below.

5.1 Maximum concrete compressive stress

In determining the plastic moments 1% steel strain was assumed. The reinforcement in the compression zone was neglected. This resulted in a maximum concrete strain of 3‰, which is below the allowable value of 5‰. The maximum concrete stress is, with 23.0 N/mm², on the failure line and corresponds to the permissible value in B45/35.

5.2 Shear resistance for punching shear failure

Aircraft impact on the roof represents a "soft missile impact". Data on a dynamic punching resistance may be found in the SRD document [9], the derivation as a semi-empirical method being given in [10]. The formula for the punching force F_p in N with an accuracy of ± 20% is:

$$F_p = 8170 \cdot (R \cdot f_{cu})^{1/3} \cdot T \cdot (3{,}14 \cdot D + 7{,}85 \cdot T) \qquad (2)$$

where:

R: Amount of reinforcement on the impact side of the slab in % as mean value of both directions

f_{cu}: characteristic concrete cube strength of cubes with sides of 150 mm length in N/m²

T: effective statical height in m

D: diameter of the loading area in m

With the following numerical values R = 0.244 %, f_{cu} = 5 N/mm² (considering the strength increase with time, T = 1.45 m, D = 3.00 m, a punching force of 56.8 MN results. As soon as the concrete resistance is exceeded, i.e. the bond between the punching cone and the rest of the concrete is destroyed, then, depending on the amount of reinforcement, there is to a varying extent a separation of the cone from the slab. The resistance of the reinforcement due to the missing shear reinforcement is then restricted to the longitudinal reinforcement, which is only really effective at relatively large strains. According to Schlüter [11] in this state the deformation of the reinforcing mesh in the region of the punching cone is in the form of a rotational paraboloid. Thus for the resistance of the reinforcing mesh $F_B(u)$:

$$F_B(u) = 2 \cdot \sin(\arctan(4u/l)) \cdot A_s^* \cdot \sigma(\varepsilon) \qquad (3)$$

with an average strain

$$\varepsilon = \varepsilon(u) = 0{,}5 \cdot (\sqrt{1+(4u/l)^2} + l/(4u) \bullet \ln((4u/l) + \sqrt{1+(4u/l)^2})) - 1 \qquad (4)$$

and the effective steel cross-section of the load resisting bending tensile reinforcement for an orthogonal mesh

$$A_s = (l/2) \bullet (a_{sx} + a_{sy}) . \qquad (5)$$

where; u: displacement in the middle of the span l, a_{sx}, a_{sy}: cross-sectional areas of steel in orthogonal directions, $\sigma(\varepsilon)$: general stress-strain relationships of the steel, l: span length of the load resisting bending tensile reinforcement ($l \approx c + 2d$ with slab thickness d, c: diameter of the impact contact area). From the numerical values a_{sx}, a_{sy} = 35.4 cm²/m, u = 0.42 m, c = 3.00 m, d = 1.50 m, which are inserted into the above formulae, the resistance of the reinforcing mesh is 19.7 MN. The sum of the resistances of concrete and reinforcement then amounts to 72,46 MN. As is evident from the summary in Fig. 3 the resistance of the slab to bending failure is much smaller than that due to shear failure.This means that with increasing load firstly the yield-lines are developed and the slab loses its load bearing capacity due to bending failure.

5. 3 Maximum shear stresses in the impact zone

The velocity of the shear wave in concrete is about 2,436 m/s. If the aircraft impacts in the middle of the slab, the waves will reach the boundary after 7.1 ms. According to the load-time diagram in Fig. 1 the load acting at this time is 39.0 MN. After the waves reach the boundaries the slab behaves as an elastoplastic SDOF system. For this case the restoring force is 33.8 MN according to Chapter 4.4, i.e. the force acting in the impact zone is at most 39.0 MN. In the impact zone the shear stress is then 1.75 N/mm². The calculated shear stress in this zone, under the influence of the punching shear load (56.8 MN), represents the limiting value and amounts to 2.5 N/mm². Thus the safety factor against shear failure is 1.45.

The investigation carried out by Eibl and Schlüter [12] with a circular slab of thickness 1.50 m shows that shear reinforcement is necessary, in order to prevent shear failure of the slab under aircraft impact. The investigated slab had a radius of 10.8 m. In comparison with the slab of the radioactive waste building (rectangular 55.5 m x 35 m) the slab is considerably stiffer, so that its fundamental frequency is also higher. In this case with the same ductility the restoring force is also higher. If the ductility were smaller the restoring force would further increase and in the limiting case of a rigid slab the maximum value of 110 MN is reached. Under these circumstances shear failure may occur before bending failure. This conclusion is in agreement with the present study.

5. 4 Maximum shear stresses in the yield-lines

The shear forces per unit length q acting on the yield-lines can be calculated using the following formula [7]:

$$q = \frac{P}{2\pi r} \tag{6}$$

r : radius of the failure zone = 17.20 m with quasi-static equivalent load of P = 33.800 MN q = 0.313 MN/m τ_c= 0.21 N/mm² with failure load P = 41.700 MN q = 0.386 MN/m and τ_c = 0.29 N/mm². According to the SIA 162 [3] the reduced shear stress represents the limiting shear stress for the slab. If the shear stresses are smaller than these values no shear reinforcement is necessary. For B45/35 the following value applies $\tau_{c,red}$ = 0.7 N/ mm². In the support zones of the slab shear reinforcement is required for permanent loads. The region of shear reinforcement has to be determined in the detailed statical analysis considering the shear stresses due to aircraft impact in order to rule out a global shear failure of the slab.

5. 5 Verification of the strain ductility

Before aircraft impact the slab still possesses elastic structural reserves. Under a concentrated load of 12.375 MN the reinforcement yields in the X direction. According to the load-time diagram in Fig. 1 this load is reached after 2.3 ms. At this time the velocity is about 4.08 m/s. The displacements determined for the uncracked concrete cross-section correspond to those of the slab with fixed boundaries: due to permanent loads 0.0129 m and aircraft impact 0.0093 m, total 0.0220 m. On yielding, on the one hand, the concrete is cracked and, on the other hand, the slab's boundary conditions change (instead of fixed they are now free to rotate). For this case the displacements under these circumstances are estimated as total 0.4772 m. The displacement ductility is then 17.0, i.e. higher than the assumed value of 10.

5.6 Verification of the rotational ductility

The experimentally determined rotational capacity is given in [13] with the following formula:

$$ru = 0.0065(\frac{d}{c}) \leq 0.07 \tag{7}$$

where: r_u: rotational capacity of the plastic hinge, d: statical depth, c: depth of the compression zone. For the given dimensions in the support area a rotational capacity of 0.02856 radians results. If this value is reached, the maximum displacement under a concentrated load is about 0.49 m. This is in agreement with the value of 0.48 m determined in Chapter 5.5. According to [14] for the given material properties and the bending moment diagrams, for limited strains the length of the plastic hinge has to be 0.32 m at the support in the X direction for the rotations of 0.02856 radians to be obtained.

6. FINAL CONSIDERATIONS

Aircraft impact on the roof slab corresponds to a plastic impulse. In addition to the above investigation the energy consideration in [13] can be adopted to verify the slab's structural resistance. With the notations

m, v_o: velocity and mass of the aircraft before impact, v_1: velocity of the aircraft after impact, V_1: velocity of the slab after impact, M_e: effective mass of the slab, and taking into consideration conservation of momentum and conservation of energy for the plastic impulse, the velocity of the slab after impact can be calculated with the following formula:

$$V_1 = \frac{\frac{m}{Me}}{1+\frac{m}{Me}}\left[v_o(1+e)\right] \tag{8}$$

If the effective mass of the slab is assumed to have 1/6 of the mass of the failed circular part (M_e = 640 t) and the mass and velocity of the aircraft is given in the HSK guideline 102 (m = 20 t, v_o = 15 m/s), V_1 is found to be 6.5 m/s. This value is comparable with that of 4.08 m/s in Chapter 5.5 determined from displacements and the load-time diagram. Here the results are strongly influenced by the assumption of the effective mass. With the velocity of 6.5 m/s the kinetic energy of the effective mass is 13.561 MNm. The strain energy capacity (SE) of the slab is given by the following formula:

$$SE = RmXe\,(\mu - \frac{1}{2}) \tag{9}$$

with Rm: statical failure load = 41.600 MN, Xe: elastic displacement under statical failure load of Rm = 0.03121 m and μ = ductility ~ 22 results SE = 27.913 MNm > 13.561 MNm. Since the SE of the slab is greater than the kinetic energy of the effective mass, the slab will resist the impact. Here, to be on the conservative side the energy destroyed by the plastic deformation of the aircraft on impact is neglected.

7. CONCLUSIONS

The present investigation is an implementation of existing theoretical and empirical know-how in a practical case. It has enabled the problem to be treated in all its aspects without resorting to a complicated nonlinear analysis. The agreement of the results from different approaches leads to the firm conclusion, that the roof slab of the radioactive waste building can withstand aircraft impact without collapse in accordance with the HSK guideline (Fig. 3).

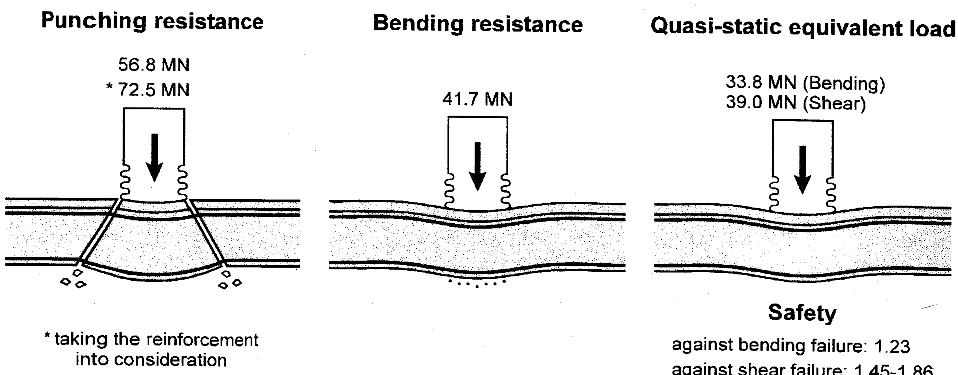

Fig. 3: Summary of the results

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