Ultimate behaviour of reinforced concrete shells under static and dynamic loading

M.Lepareux, Ph.Matheron, Ph.Jamet, J.L.Lieutenant, J.Couilleaux & G.Lazare-Chopard
C.E.A., CEN/Saclay, IRDI/DEDR/DEMT/SMTS/LAMS, Gif-sur-Yvette, France
J.Rivière
C.E.A., CEN/Fontenay aux Roses, IPSN/DAS/SAM, France

I. INTRODUCTION

Safety analysis of nuclear plants implies situations where concrete structures are subjected to extreme loadings such as impacts. The evaluation of margins requires a good definition of the ultimate state of such structures. This problem has already been considered in a previous study [1], where the mode of failure was essentially dominated by flexion. The problem of punching is now considered. The main objectives of the study is to obtain experimental data to validate finite elements results under static and dynamic loading, and to formulate a simple method which can be applied at a dimensionning level. The case of slabs with a central square aperture is also treated.

II. STATIC LOADING OF SIMPLE SLABS

II.1 Experiments

The dimensions of the reinforced concrete slabs are 1.8 m × 1.8 m × 0.125 m. The reinforcement is presented by figure 1. The slabs were simply supported at the middle of their edges. The load is applied through a steel disk, by an actuator. The displacement rate was constant and equal to 0.05 mm/s. The applied force and the displacements at various locations were continuously monitored. Tests were performed with 3 different disks : ϕ 150 mm, ϕ 200 mm, ϕ 280 mm. In the three cases, punching occured before the ultimate flexural load was reached (figure 2). During the tests, typical flexural cracks appeared at the lower face of the slabs, their observation showed that punching occurs for a force which tends to be closer to ultimate flexural load, when the disk diameter increases.

II.2 Numerical studies

Numerical analyses were performed using global plasticity [2] : The reinforced concrete is represented by an equivalent homogeneous material. Its properties are determined by the pre-processor SAMSON, using the properties of concrete and steel. The analysis itself is then performed with shell elements using the BILBO code of the CASTEM Finite Element System [3].

Figure 3 shows the dsiplacement at the center of the slab versus the applied force for one configuration, comparison between experimental and numerical results is also presented. The agreement is satisfactory, it provides a good validation of the global plasticity method for such configurations, and for flexural deformations. The phenomenon of punching is obviously not taken into account by the analysis.

II.3 Interpretation using simple models
II.3.1. Ultimate flexural load

Ultimate flexural load can be estimated using the slip line approach [4]. The selected deformation mechanism has a conical shape, with one circle corresponding to the support points of the slab, and a smaller circle corresponding to the loading disk. This assumption leads to the following expression :

$$F_b = 7.05 \frac{1}{1 - a} F_{ML} \quad (1)$$

with F_b : ultimate flexural load
l : length of the slab edges
a : diameter of the loading disk
F_{ML}: force corresponding to the limit moment of the equivalent homogeneous material (computed by SAMSON).

II.3.2. Punching load

The punching load is computed using the french regulatory code BAEL 80 [5]. The following expression is used :

$$F_p = 1.5 \times 0.045 \times f_{cj} \times \Pi(a+h) \times h \qquad (2)$$

with F_p : punching load
f_{cj} : compressive strength of concrete
h : slab thickness
a : disk diameter

II.3.3. Interaction between flexion and punching

The results obtained using the expression (1) and (2) are presented by the following table :

ϕ disk (mm)	f_{cj} (MPa)	$F_{experiment}$ (Kn)	F_p (Kn)	F_b (Kn)	F_{exp}/F_p	F_{exp}/F_b
280	45.4	338	487	322	0.69	1.05
200	49.2	265	425	305	0.62	0.87
150	49	232	357	296	0.65	0.78

The results show a possible interaction between flexion and punching. They are presented in a different way by figure 4. New tests will be performed to determine an interaction curve inside which the structure is safe.

III. DYNAMIC LOADING OF SIMPLE SLABS

III.1 Experiments

Two dynamic tests were performed on simple slabs with 150 mm diameter loading disks.

The experimental set-up was already presented [1], it allows to drop projectiles of different masses from different heigth.
The obtained results are presented by the following table :

Projectile mass (kg)	Impact speed (m/s)	Energy (J)	Punching
103.5	6.62	2720	no
204	6.53	4530	yes

After the test with the lowest energy, circumferential cracks were observed, they show that punching was nearly reached.

III.2 Numerical studies

The studies were performed with the explicit code PLEXUS [5]. The projectile is modeled as a rigid disk, in which the total impacting mass is concentrated. This method allows to obtain the impact parameters (impulsion, force, multiple impacts) and is more efficient than adding masses to the structure.
Comparison between experimental and numerical results shows a satisfactory agreement, as presented by figure 5, for two displacements corresponding to symetrical locations in the slab. However, the reaction forces versus time curves have different shapes in the computation, when compared to experimental data.
An interpretation using simple models is now tempted. It is based on an interaction diagram using equivalent static quantities.

IV. SLABS WITH CENTRAL SQUARE APERTURE

The outer dimensions of these slabs are identical to the previous ones. The square aperture is 0.6 m × 0.6 m. The reinforcement is identical to the previous one outside a square of 1.2 m edge, it is doubled inside, up to the aperture edges.
Tests were performed with a rigid steel plate (0.745 m × 0.745 m outside dimensions) covering the aperture.
Under static loading ultimate behaviour is governed by a flexural mechanism. This conclusion is confirmed by analyses. Two different assumptions were considered for the computations :
- imposed displacements at the corners of the steel plate,
- imposed displacements along the edges of the steel plate.

Figure 6 presents some of the obtained results. It shows that the true loading condition is probably in between the two considered cases.
Application of the BAEL expression for punching gives a load of 1130 Kn. Comparison with the obtained results confirms that ultimate behaviour of the structure is governed by flexural mechanisms.
Dynamic tests were also performed. They show that the ultimate behaviour is identical to the one observed under static loading.

V. CONCLUSION

The study undertaken has provided reference experimental data concerning ultimate behaviour of reinforced concrete slabs under static and dynamic loading.

Comparison between experimental and numerical results led to a good validation of the SAMSON, BILBO and PLEXUS codes from the CASTEM Finite Element System. A simple method is proposed to account for interaction between flexion and punching. Additionnal tests will be performed in the future to validate this method.

REFERENCES

[1] Hoffmann A., Jamet Ph., Lepareux M., Millard A., Barbé B., Maurel P. Ultimate flexural behaviour of reinforced concrete shells under static and dynamic loading - Paper J1/8 - SMiRT 8, 1985

[2] Hoffmann A., Millard A., Nahas G. Application of a global plasticity model to determine the ultimate strength of a reinforced concrete slab - Paper J3/7, SMiRT 7, 1983

[3] Jeanpierre F., et al. CEASEMT - System of finite element computer programs - IAEA/IWGFR Specialist's meeting on high temperature structural design technology of LMFBRs - Champion, Pa, 1976.

[4] Nielsen M.P. Limit analysis of reinforced concrete slab - Acta polytechnica Scandinavia - CI 26, Copenhague, 1964

[5] Règles techniques de conception et de calcul des ouvrages et constructions en béton armé suivant la méthode des états limites. Règles BAEL 80 - Editions Eyrolles, 1980.

[6] Hoffmann A. and al. PLEXUS a general computer program for fast dynamic analysis. Proceeding of the Conference on Structural Analysis and Design of Nuclear Power Plants, Porto Alegre - Brasil, 1984

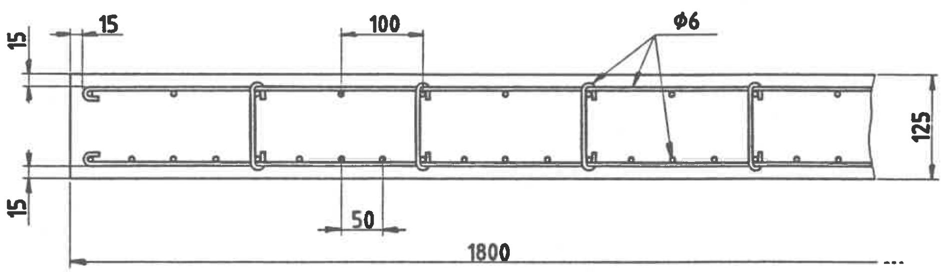

Figure 1 : Simple slab-reinforcement

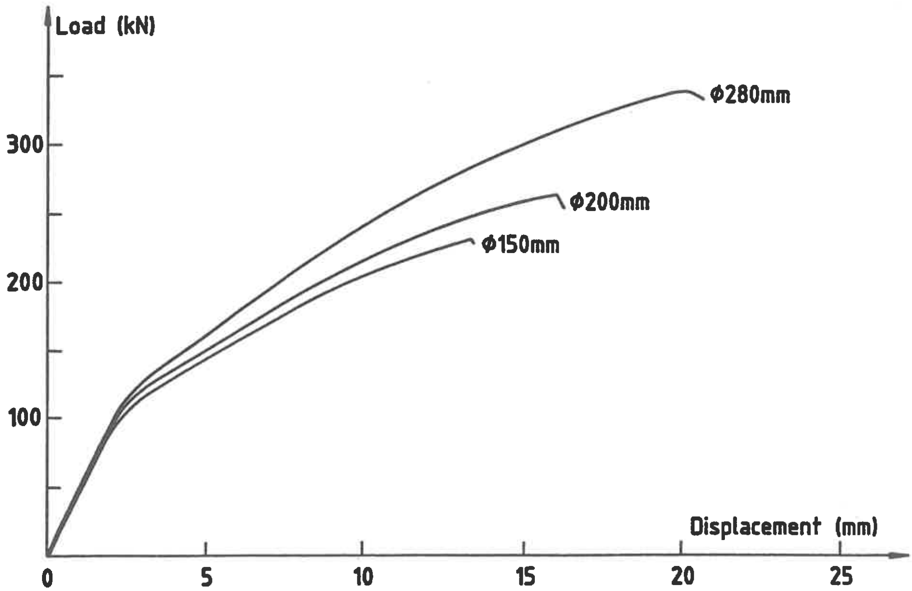

Figure 2 : Simple slabs-static tests.

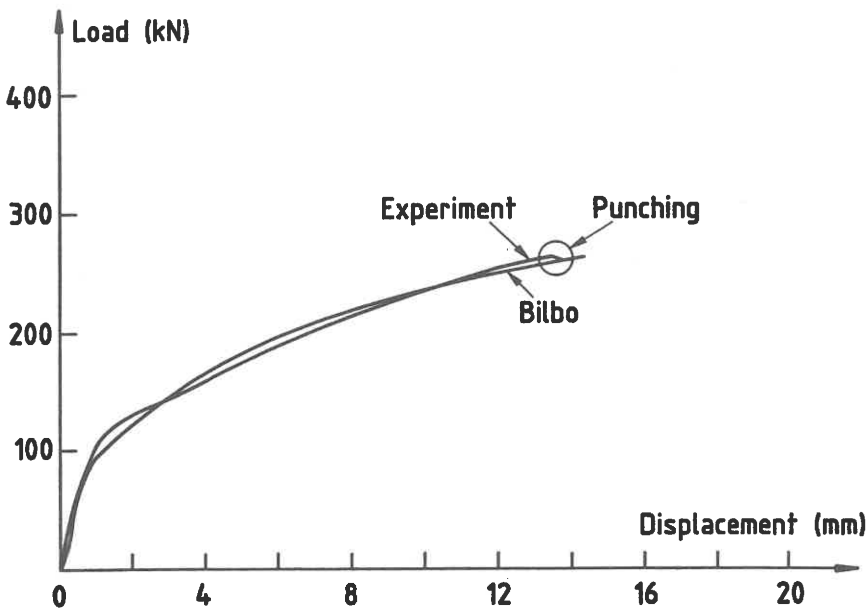

Figure 3 : Comparison between test and numerical analysis (simple slab - ϕ 200 mm).

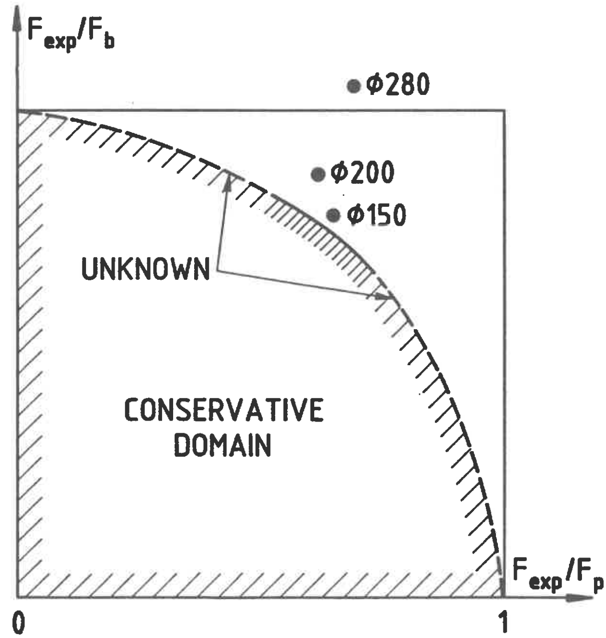

Figure 4 : Interaction punching-bending

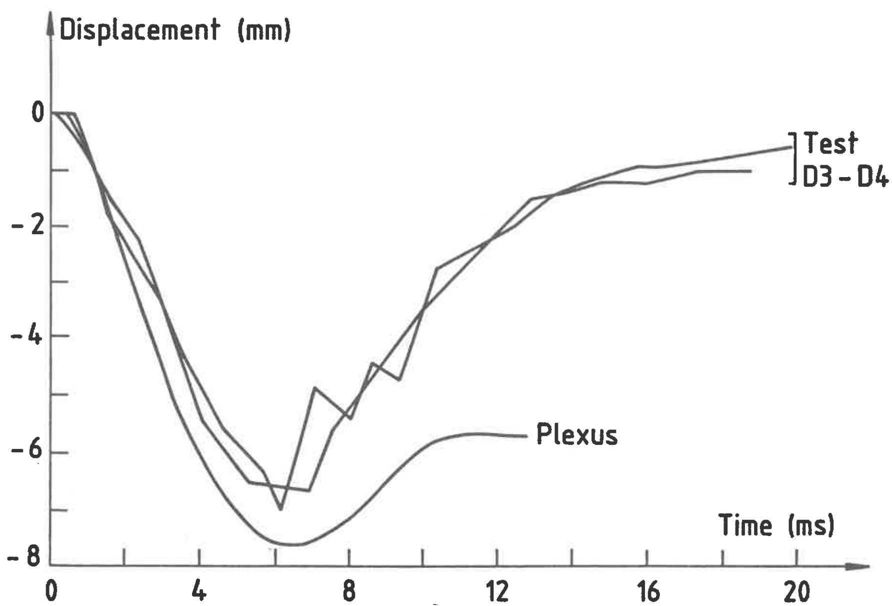

Figure 5 : Comparison between test and numerical analysis (simple slab - plate ϕ 150 mm, E = 4350 J - Perforated)

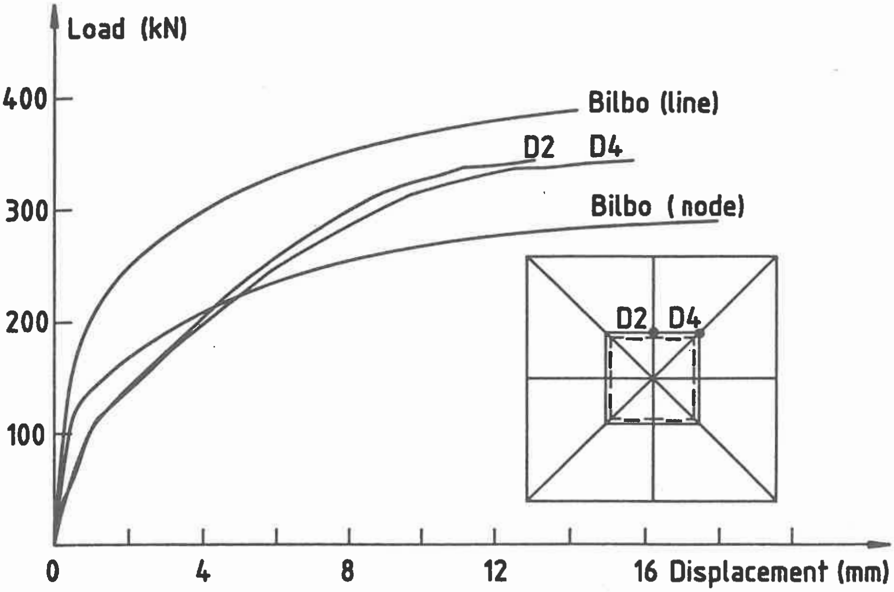

Figure 6 : Comparison between static test and numerical analysis (slab with square aperture)