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► **To cite this version:**

L. Ågårdh. Fe-Modeling of Fibre Reinforced Concrete Slabs Subjected to Blast Load. Journal de Physique IV Proceedings, 1997, 07 (C3), pp.C3-723-C3-728. 10.1051/jp4:19973123 . jpa-00255409

HAL Id: jpa-00255409

<https://hal.science/jpa-00255409>

Submitted on 4 Feb 2008

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FE-Modeling of Fibre Reinforced Concrete Slabs Subjected to Blast Load

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Abstract: Fiber reinforced concrete elements are used as protection against blast loads and fragments. The present project is aiming at an accurate FE-modelling of the behavior of such elements loaded by transient dynamic loads. Thus blast experiments on thin slabs, hard and soft impacts on beams of different sizes with and without fibres, form the basis of experimental results. The codes used are LS-DYNA and ABAQUS/Explicit with various material models, e.g. the "Winfrith" concrete model for LS-DYNA and the "Constitutive model for brittle cracking" in ABAQUS/Explicit. In the present paper the experimental results from blast loads on slabs are presented with results from some FE-simulations.

Resume': Les éléments de béton armés en fibres sont utilisés dans la résistance contre les décharges explosives et l'impact de fragments. La présente étude a pour objectif d'établir une modélisation par Eléments Finis du comportement de tels éléments soumis à des excitations transitoires. Ainsi, les résultats expérimentaux sont tirés d'expériences d'explosion sur des plaques de faible épaisseur, et d'impacts plus ou moins forts sur des poutres de différentes tailles, comprenant ou non des fibres. Les programmes utilisés sont LS-DYNA et ABAQUS /Explicit avec différents modèles de matériaux, comme par ex: - le modèle "Winfrith" du béton dans le cas de LS-DYNA, - le "Modèle Constitutif des Criques" dans le cas de ABAQUS/Explicit. Ce compte-rendu présente les résultats expérimentaux d'explosions effectuées sur plaques, ainsi que les résultats de simulations par Eléments Finis.

1. INTRODUCTION

Numerical methods in prediction of structural response to blast and impact loads are inevitable. To simulate the response of structural elements with an acceptable degree of accuracy and validity, the material failure mechanisms should be fully understood and implemented in the codes used. For brittle materials like concrete, generally validated material models in commercial FE-codes seems to be rare. One cause for this is, that those models are time-consuming to run in a 3D FE-code. Another cause is, that sophisticated models often need "too many" and sometimes "non measurable" parameters for a proper material description.

For users, who do not develop their own material models, the choice of model is a matter of optimization. For a fair accuracy in transient dynamics the concrete model should take "strain rate" effects into consideration. Furthermore the crack initiation, failure localisation and failure modes need to be mastered without disturbing mesh dependency. Options for reinforcement description and bonding in a pragmatic way is desirable, if the code is to be used in practical design. Thus there is a trade off between the requirements of accuracy in the predictions, accessibility to material models and the feasibility in feeding the model with proper data. A judicious choice needs a solid background of new and relevant research results, [1]-[4].

In the present paper the validity of some numerical FE-models is investigated and simulations are compared to results from blast experiments on steel fibre reinforced concrete (FRC) slabs, [5]. The codes used were LS-Dyna, [6] with the "Winfrith-model", [7] and ABAQUS Explicit, [8] with the "Brittle Crack Model", [9]. The Winfrith-model is a smeared crack and a smeared reinforcement model with a default Equation of State. The strength enhancements due to the rate effect is included in the model. The Brittle Crack Model has a smeared crack assumption, a fixed direction crack alignment and a linear elastic response in compression. No strain rate effect is included in the model.

2. EXPERIMENTS

Four series of three reinforced, clamped FRC slabs, were subjected to various amount of blast loading in a shock tube to establish the response. The dimensions were 1.2 · 1.2 · 0.06 m with conventional reinforcement in two perpendicular directions. The concrete used was of the type: "OPTIROC, Steel Fibre Bridge-Deck Concrete". The specifications are: Cement type: "Std P". Aggregates: "Porfyr" 0-20 mm. Steel fibers type: "Dramix ZC 30/50", 55 kg/m³ fresh concrete. Proportions: 440 kg cement/m³, Group K80 T (SBN, Swedish Regulation). Cube strength (Nominal) 90 Mpa. Water 7.6 %, wct = 0.38, Air 5-7 %. The concrete was tested at Swedish Testing and Research Institute with the following results:

Cube strength (100 mm, compression)	63.2 ± 1.3 MPa
Cylinder strength (D = 100 mm, h = 150 mm)	86.1 ± 10.7 MPa
"Brazilian test" (Cube 150 mm)	6.1 ± 0.3 MPa
E-modulus (ISO, loading rate 0.6 MPa/s)	52.9 ± 7.6 GPa
E-modulus (CEB FIP, loading rate 0.6 MPa/s)	42.8 ± 5.3 GPa

The fibre reinforcement ratio is 0.7 %, from which the fracture energy is estimated to 2500 N/m, [10]. The conventional reinforcement, equal in both directions, was steel KS40, 14 Φ8 c 0.08 m in a square pattern giving a reinforcement percentage $\mu = 0.97$ %. Nominal yield stress = 400 Mpa. Covering layer $d = 0.011$ m. Small steel blocks were spot welded to the reinforcement for the attachment of accelerometers. The reinforcement was wired. The slabs were tested about 2 month after casting.

The slabs were clamped at the fixture in the shock tube with hydraulic jacks with a pressure of 11 MPa. The pressed parts were carefully plastered in advance, but micro cracking might have occurred due to initial skewness of the slab. The degree of clamping was estimated by the help of frequency measurements to 27 % in average. The explosive charge was placed in the middle of the tube section, at a distance of 20 m to obtain a plane pressure wave on the slab. The explosive charge was of a plastic type.

Four 60 mm strain gauges, two horisontal (x), two vertical (y), and four accelerometers (z), were glued to the back side of each slab, close to the 1/3-points of the free slab. For the measurement of center displacements a non contacting displacement device was fixed at the foundation. Different types were used, depending on the expected range of displacements. For the A-series a KAMAN KD-2300-6C was used. The measurement range was 6 mm with a frequency limit 50 kHz. For the B and C series a similar type KD-2300-12C was used with a range of 0-50 mm. For the D-series a mechanical device was tested.

A "Side-On" pressure gauge (Kistler 7031, 0-25 MPa) was mounted in the tube wall about 0.3 m from the slab and used as reference for the pressure. To obtain proper values of the load level and to check the distribution of pressures over the surface, blast tests were made with a wall consisting of a 250 mm thick steel plate clamped in the fixture. At the surface of the wall, 9 pressure gauges were attached to measure the reflected pressure front. For three charge levels, 0.25, 2.0 and 5.0 kg, the reflected pressure front was measured together with the "Side On"- pressure. By this registrations, proper load curves was established for the simulations. The acquisition system used was manufactured by Maurer Instruments, Switzerland 1989, type "Analog to Digital Acquisition Memory". Sampling frequency used was 100 kHz.

The first series of slabs A1-A3 were loaded by a charge of 0.5 kg. Frequency measurements showed that small changes in the resonant frequencies had occurred after the test. Thus in the next series of slabs, the first charge was chosen to 0.25 kg, series 1B1-1B3, and immediately after for the same slab, the next charge was 0.75 kg, series 2B1-2B3. At the first load level, frequency analysis showed that the behavior was linear within measurement accuracy. The series, C1-C3, was subjected to a charge of 2.0 kg. The last series was used to establish the damage level. Thus the slabs D1-D3 were loaded with respectively 5 kg (too much), 3 kg (not enough) and 4 kg charges, (on the limit of destruction).

3. RESULT FROM THE EXPERIMENTS

In Figs. 1 - 4, the centre displacement histories for the series A - C are shown in diagrams.

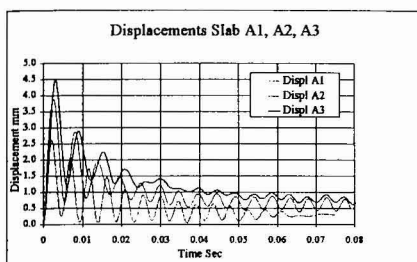


Figure 1: Center displacement in series A

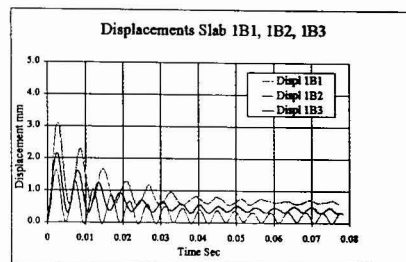


Figure 2: Center displacement in series 1B

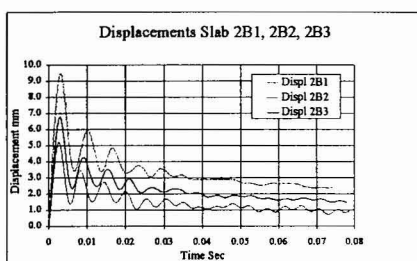


Figure 3: Center displacement in series 2B

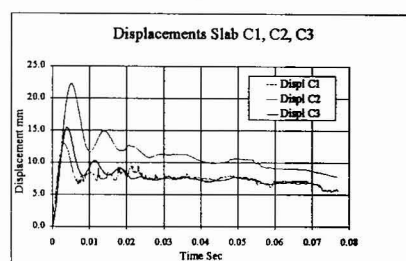


Figure 4: Center displacement in series C

In Tab.1 below, measured peak data are presented. The displacement measurement system failed to catch the high velocity displacements in series D. The resonant frequencies are determined from the energy spectral density of the displacement signals.

Table 1: Peak values from the centre displacement histories. Strains and accelerations at 1/3-points.

Slab No	Charge	Peak pressure	Duration phase I	Peak displ.	Resonant freq.	Peak velocity	Peak accelerat.	Strain ϵ_x	Strain rate $\dot{\epsilon}_x$	Strain ϵ_y	Strain rate $\dot{\epsilon}_y$
	kg	Mpa	ms	mm	Hz	m/s	g	%	%/s	%	%/s
A1	0.5	0.32	60	2.6	217	1.8	288	0.48	537	0.26	289
A2	0.5	0.31	50	3.9	214	2.4	363	0.48	461	0.84	412
A3	0.5	0.31	60	4.5	215	2.0	343	0.36	419	1.00	1150
Aver. A	0.5	0.27	57	3.7	215	2.1	331	0.4	472	0.7	617
1B1	0.25	0.19	50	3.1	208	1.5	225	0.52	379	0.58	452
1B2	0.25	0.20	50	1.6	213	0.9	215	0.23	249	0.41	349
1B3	0.25	0.19	50	2.2	210	1.1	225	0.24	230	0.73	522
Aver. 1B	0.25	0.20	50	2.3	210	1.2	222	0.3	286	0.6	441
2B1	0.75	0.43	66	9.5	209	4.0	433	0.96	908	1.99	1388
2B2	0.75	0.43	70	5.2	220	2.8	440	0.52	630	1.37	784
2B3	0.75	0.43	70	6.8	216	3.2	460	0.68	915	1.76	1543
Aver. 2B	0.75	0.42	69	7.2	215	3.3	444	0.72	818	1.71	1238
C1	2.0	0.80	70	13.1	235	5.9	895	1.51	1358	1.80	2353
C2	2.0	0.79	70	22.0	205	6.6	910	1.73	1475	1.86	3978
C3	2.0	0.74	70	15.4	217	5.3	780	1.72	1025	1.98	2208
Aver. C	2.0	0.77	70	16.8	219	5.9	862	1.65	1286	1.88	2846
D1	5.0	1.37	60	*****	*****	*****	1600	*****	*****	4.00	3478
D2	3.0	1.13	55	23	*****	6.6	1700	1.30	873	1.15	1757
D3	4.0	1.26	50	*****	*****	*****	1425	*****	*****	*****	*****

The peak values in Tab 1. show large deviations from the averages. The deviations in the displacement peaks (30%) are mainly due to the small values that was measured considering the scale of the slabs and fixtures etc. but also to variations in the individual elements at manufacturing and clamping. In the comparisons with predicted results the averages will be used. The strains and strain rates results scatter with several outliers, although measured at points on the slab where small strains were expected. Cracks and bond slips under the strain gauges contribute to these deviations. The conclusion is that strain measurements on concrete close to the tensile limit opens for interpretation problems. The maximum strain rates are calculated from the strain "front signal" as difference ratios. They give a fair estimation of the maximum strain rate the measurement point was subjected to.

The limiting capacity of the slab was found to be the load corresponding to a charge of 3 kg and the proportional limit of the slab to the load corresponding to a charge of 0.25 kg. Spalling for 4 kg and 5 kg charges was observed. See Figs. 5-6. At the load from the charge of 3kg, only small cracks were visible.

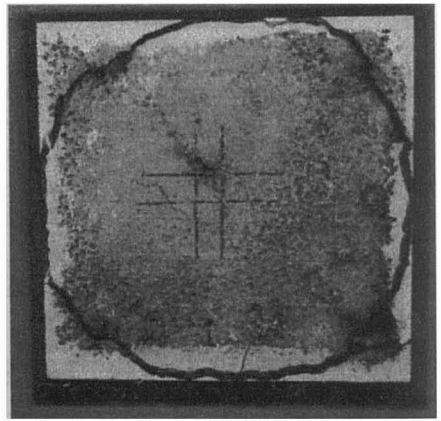
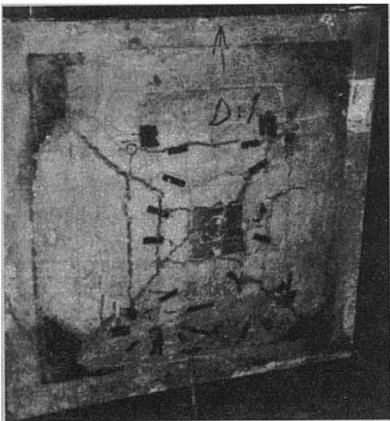


Figure 5: Slab D1, front. Blast load from charge 5kg /20m. **Figure 6:** Slab D1, back. Blast load from charge 5kg /20m.

4. FE-MODEL

For the modelling of transient dynamic response, an explicit version of a FE-code is needed. For this project, LS-DYNA with the Winfrith model and ABAQUS/Explicit with the Brittle Cracking Model was used. Frequency measurements have shown, that the slabs were not completely clamped, so the fixed part of a slab, see Fig. 12, was modelled as a linear elastic material, the stiffness of which was 15 GPa. This gives about the same resonante frequency as the average, 215 Hz, see Tab.1. The clamped part was then modelled as a simply supported beam, see Fig. 7. The model (1/4 of the slab) consists of 2420 8-node brick elements in 5 layers, connected in 1174 nodes.

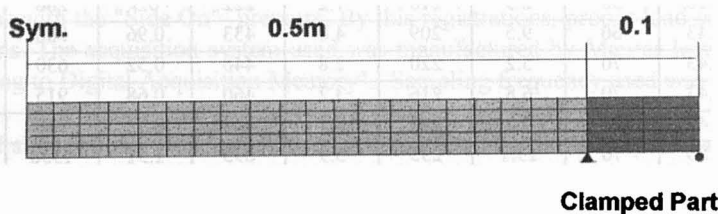


Figure 7: Section of the FE-model showing the modelling of the clamped part.

In the input data set for the Winfrith model, the fracture energy according to CEB should be used. It is questionable however, if the sample test procedure for fracture energy is useful for FRC beams, [10].

In Figs. 8-9 the displacement histories from a calculation with ABAQUS / Explicit are shown. In Figs. 10-11 corresponding displacement histories from a calculation with LS-DYNA and the Winfrith model. In Tab. 2 peak values from two different codes and material models are compared to the experiments.

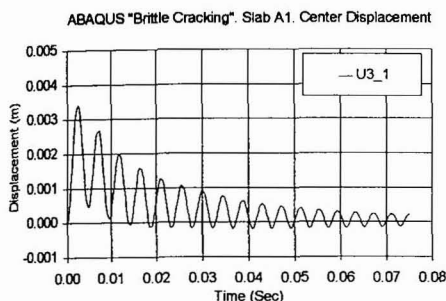


Figure 8: ABAQUS Displacement series A. Charge 0.5 kg

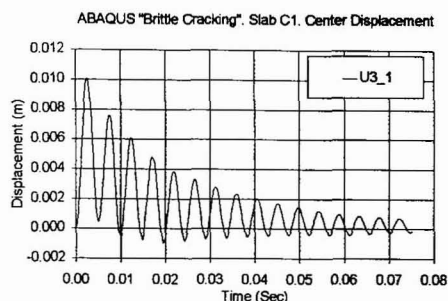


Figure 9: ABAQUS Displacement series C. Charge 2 kg

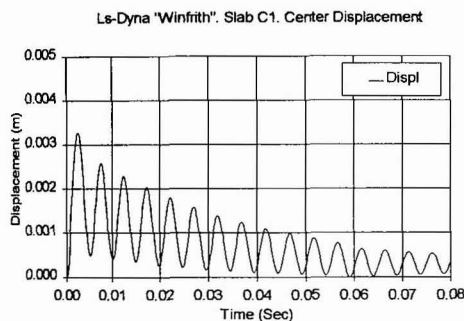


Figure 10: LS-DYNA. Displacement series A Charge 0.5 kg

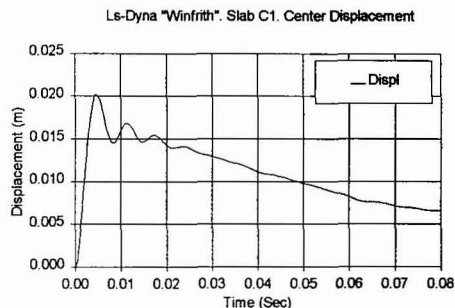


Figure 11: LS-DYNA. Displacement series C. Charge 2 kg.

Table 2 : Comparison between experiment and simulation. Note that C stands for "Centre".

Slab No	Peak displ Exper. **	Peak displ ABAQUS	Peak displ LS-DYNA	Str. rate Exper. **	Str. rate C ABAQUS	Str. rate LS-DYNA	Peak acc Exper. **	Peak acc C ABAQUS	Peak acc LS-DYNA
	mm	mm	mm	S / sec	S / sec	S / sec	g	g	g
A1	3.7 (26%)	3.4	3.4	0.5 (56%)	9.4	0.86	331 (12%)	240	*
1B1	2.3 (33%)	1.5	1.4	0.4 (31%)	4.0	0.56	222 (3%)	195	*
2B1	7.2 (30%)	4.8	4.8	1.0 (35%)	5.5	1.12	444 (3%)	450	*
C1	16.8 (27%)	10.0	21.0	2.1 (52%)	10	2.29	862 (8 %)	1450	*
D2	23	15.5	Failure	1.3	14	Failure	1700	2750	*
D3	***	18.0	Failure	***	20	Failure	1425	9000	*

* The algorithm for calculation of accelerations is questionable. ** In parenthesis: (Variation coefficient)

*** Measurements missing.

The results in Tab.2 show, that the numerical simulations of the centre displacements compared to corresponding experimental averages are within the deviation limits with few exceptions. Both codes could predict the collapse of the slab D1 loaded with the charge 5 kg. The Winfrith model predicted also the failure of D3. The "survival" of D2 was predicted by ABAQUS. The strain rates and the accelerations (C1 and D) were not well predicted by ABAQUS. The accelerations were not predicted at all by LS-DYNA, a fact that has something to do with the diagonal mass matrix and the central difference algorithm used in the time integration.

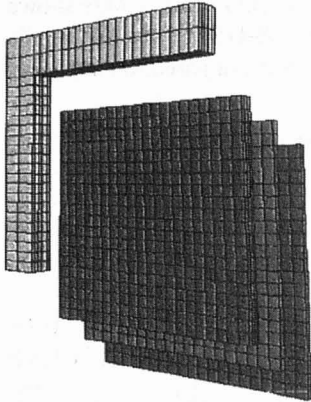


Figure 12: FE-model of 1/4 of the slab.

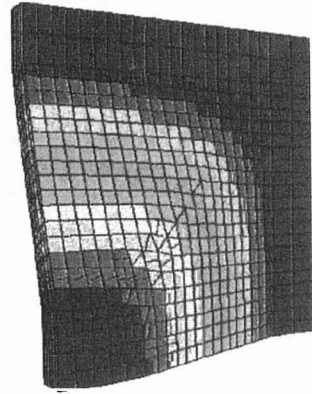


Figure 13: Fringes of z-displacement and crack patterns.

5 CONCLUSION

The research project reported here is at an early stage. Blast experiments in a shock tube on steel fibre and conventionally reinforced concrete slabs have been performed in order to validate codes and material models. Numerical modelling has been done with ABAQUS with the "Brittle Crack" model and with LS-Dyna with the "Winfrith" model. The simulations turn out to give fairly accurate results for some variables, like displacements for low loads and the ability to predict the failure loads in the specific cases reported here. The strain rate effect was however not significant due to the large distance between the slabs and the charges.

6 ACKNOWLEDGMENTS

To Dr. Jan Hernelind FemTech AB, who ran the Abaqus/Explicit code, to my friend M. Michel Gascoin, who translated the abstract and to my colleagues at FOA, I am indebted for their support in this project.

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