

# ANALYSIS OF THE FRACTURE OF REINFORCED CONCRETE FLAT ELEMENTS SUBJECTED TO EXPLOSIONS. EXPERIMENTAL PROCEDURE AND NUMERICAL VALIDATION

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## RESUMEN

Muchos de los modelos de comportamiento de material más utilizados en la simulación numérica del hormigón sometido a altas velocidades de deformación han sido desarrollados originalmente para la simulación de impacto balístico. Por lo tanto, éstos son modelos basados en la teoría de la plasticidad en los que el tratamiento del comportamiento a compresión es muy complejo, mientras que el criterio de fallo a tracción se simula de una forma bastante más simple. Dado que los elementos de hormigón armado sometidos al impacto de la onda expansiva de una explosión presentan generalmente un fallo por tracción, cabe la posibilidad de que los modelos de material habituales para el hormigón a altas velocidades de deformación no representen adecuadamente su comportamiento. En este trabajo se presenta un programa experimental en el que se han ensayado elementos planos de hormigón armado ante explosiones. En total se han llevado a cabo cuatro detonaciones, en las que se han ensayado 12 placas de dos hormigones diferentes ante la misma carga explosiva. Los resultados del programa experimental se utilizan para el desarrollo y el ajuste de herramientas numéricas necesarias para la simulación de elementos de hormigón sometidos a explosiones.

## ABSTRACT

Many of the material models most frequently used for the numerical simulation of the behavior of concrete when subjected to high strain rates have been originally developed for the simulation of ballistic impact. Therefore, they are plasticity-based models in which the compressive behavior is modeled in a complex way, while their tensile failure criterion is of a rather simpler nature. As concrete elements usually fail in tension when subjected to blast loading, available concrete material models for high strain rates may not represent accurately their real behavior. In this research work an experimental program of reinforced concrete flat elements subjected to blast load is presented. Altogether four detonation tests are conducted, in which 12 slabs of two different concrete types are subjected to the same blast load. The results of the experimental program are then used for the development and adjustment of numerical tools needed in the modeling of concrete elements subjected to blast.

**KEYWORDS:** Reinforced concrete, blast, numerical simulation.

## 1. INTRODUCTION

The behavior of reinforced concrete elements when subjected to explosions is a topic of major concern for research in both civil and materials engineering, given the vulnerability to accidental and intentional explosive incidents of civilian buildings with reinforced concrete structures.

Proper simulation of structural elements needs good skills in material modeling under high strain rates. The success in the use of numerical tools for assessment of structural response is highly dependent on the equation of state and constitutive models selected for the simulation of the material behavior [1].

Several material models have been developed for the prediction of concrete behavior when subjected to high strain rates, which implemented on commercial finite element software. The Concrete Damage Model [2], Winfrith Concrete Model [3] - [5] and Johnson-Holmquist Concrete Model [6], among others, are currently implemented on LS-DYNA [7]. On the other hand, Autodyn [8] offers the Gebbeken-Ruppert Model [9], partly based on the above mentioned Johnson-Holmquist Concrete Model.

All these material models are plasticity-based models that uncouple hydrostatic from deviatoric components of the stress tensor. In the development of these models, a matter of major concern has been their capability of predicting the compressive behavior of concrete and,

therefore, equations of state for describing the relation between the hydrostatic pressure and the volumetric strain must be set for all of them. They also present a three invariant dependent failure surface, developed after the fitting of biaxial and triaxial static compressive tests. The definition of these models allow them to represent accurately the complex compressive behavior of concrete, which is usually depicted by an elastic branch limited by a yield or failure criterion followed by plastic flow or post-failure behavior [10]. Such treatment of the compressive behavior, in turn, leads these models to be dependent on multiple parameters, with measurement of some of them not being possible by experimental procedures.

Contrarily, in these models tensile behavior is usually modeled in a simple manner, usually by cut-off or maximum principal stress criteria followed sometimes by a softening behavior.

In all the previously referred models strain rate enhancement factors are mainly based on the CEB report No. 187 [11] and the results obtained by Zielinski and Reinhardt [12], as well as Bischoff and Perry [13], which rely on experimental records of concrete subjected to high strain rates on Split Hopkinson Pressure Bar devices.

To sum up, there exist a wide variety of material models for the simulation of concrete behavior under high strain rates. Most of them present a very detailed and complex treatment of the compressive behavior, while tensile behavior is usually neglected or treated in a very simple manner. One reason for this fact may be that they were originally developed for modeling ballistic impact, where compressive behavior of concrete plays a major role.

Therefore, the applicability of such material models to blast load response of concrete elements is not clear. Besides, these models must be fed with an enormous amount of material parameters which are usually not easy to measure or estimate.

Consequently, a reliable and cost-effective methodology is needed for testing reinforced concrete samples. In this work, a novel experimental set-up was devised. It allows the simultaneous testing of up to four concrete samples. This way the experimental scatter is greatly reduced. In addition, numerical modeling of the detonation tests was carried out. Two different material models were used to simulate the behavior of concrete. The numerical results are in good agreement with the experimental measurements.

## 2. EXPERIMENTAL PROGRAM

### 2.1. Experimental set-up

An experimental set-up for testing planar reinforced concrete elements under blast load was designed. Its principal design criterion was that the set-up must be

able to test up to four slabs with each detonation, with all of them being loaded identically.

To that end, a steel frame to support the concrete specimens was built for open air detonation tests, consisting of four vertical columns tied horizontally with beams that also withstood the concrete slabs. The slabs were placed on vertical planes equidistant to the explosive. To avoid shock reflections, the device was designed in such a way that the slabs were placed with their height over the ground being greater than their distance to the explosive.

Hanging the explosive in the center of the steel frame assured that all the slabs received the same shock wave pressure history. This set-up allowed testing up to four specimens in each detonation shot, with the following characteristics: (a) all the specimens were loaded identically and (b) a reliable result was provided, given the number of specimens sufficed for a statistical sample. Besides, costs on explosives, explosive handling and time expenses on tests were strongly reduced.

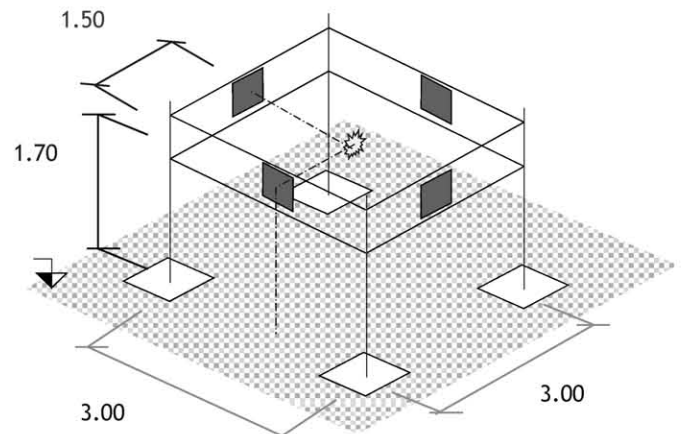


Figure 1. Schematic view of the experimental set-up.

Dimensions of the steel frame were set to 3.00m between columns, stand-off from explosive to the slabs to 1.50m, and height of the center of the slabs to the ground 1.70m (Fig. 1).

### 2.2. Experimental procedure

Concrete square-shaped slabs of 500 x 500 x 80 mm were cast using two different types of concrete, namely normal strength concrete (NSC) and high strength concrete (HSC). Control samples of a cylindrical shape of diameter 150mm and height 300mm of both concrete types were also cast for compressive strength tests at different concrete ages.

Reinforcement was placed on the back side of the concrete slabs, consisting of a steel mesh of bars of 6mm diameter of steel grade B 500 S, spaced 150mm in both directions. Dimensions of the specimens are shown in Fig. 2.

Altogether four detonation tests were conducted, in which 12 slabs (six of each concrete type) were subjected to a 5.712kg of Goma 2 ECO explosion, equivalent to a 5kg TNT explosion. As the stand-off distance was 1.50m, the scaled distance was  $0.88\text{m}\cdot(\text{kg TNT})^{-1/3}$ .

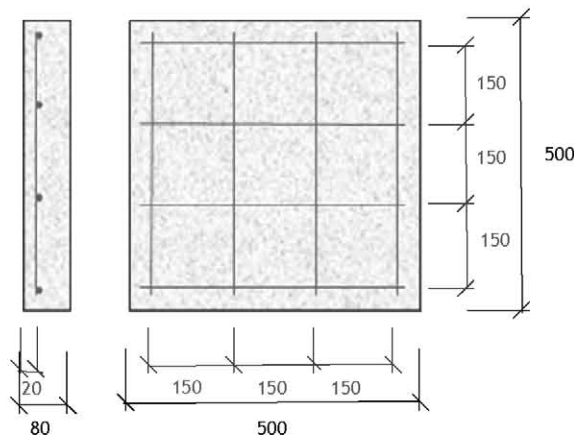


Figure 2. Test specimen geometry and reinforcement details (dimensions in mm).

In each detonation three concrete slabs of the same concrete type, plus an aluminum control plate, were tested. The aim of this control plate was to provide a specimen with the same exposed area to the blast load as the reinforced concrete slabs, though made out of a perfectly homogeneous ductile material with a well-known stress-strain relationship.

### 2.3. Experimental results

The response of the reinforced concrete slabs under the shock wave was the same for all the slabs, that is to say: (1) slabs bent on their corners under shock wave impact, (2) tensile failure of concrete occurred on the rear slab side, where failure modes of bending, shear and mixed modes were present on the slab sample, (3) slabs bounced on their boundary conditions and fell down from the beams to the center of the steel frame.

The theoretical failure mode after the yield-line method of a square-shaped slab supported on its four corners when subjected to a uniformly distributed static load is of a bending mode, described by a cruciform cracking pattern centered on the back side of the specimen, with lines being parallel to the sides of the slab.

However, from the results obtained in these detonation tests (listed on Table 1, see Fig. 3), it can be inferred that the shear failure with circular-like cracks centered on the boundary steel support plates dominated the response of the tested slabs.

Table 1. Failure modes of concrete slabs

Concrete type	Failure mode (number of specimens)		
	Bending	Shear	Mixed
NSC	1	5	0
HSC	2	2	2

It has been stated that concrete elements whose failure mode under static loading is of a bending type may switch to a shear failure when subjected to fast dynamic, impulsive loading [11], [14] - [17]. The reason is that the impact wave moving outward from impacted surface may cause shear failure before any noticeable bending occurs. This behavior may be blamed on crack propagation velocity, as well as on inertia forces effects, and is of great importance given that shear failure mode is a more brittle failure than the bending mode.

## 3. NUMERICAL SIMULATION

### 3.1. Description of developed models

One of the aims of this experimental benchmark was to provide experimental data for the development and adjustment of numerical tools for the modeling of concrete elements subjected to blast loading. The numerical analysis of the detonation tests was carried out using LS-DYNA [7], an explicit dynamic finite element software based on the central difference integration rule, suitable for impulsive loads and strong discontinuous responses.

Concrete and support steel plates were meshed with 4x4x4mm one point integration solid (brick) elements, resulting in a total of 546000 elements. Steel rebars were input by 1500 beam (truss) elements of 4mm length, with its bond with concrete being set through common nodes between solid and beam elements.

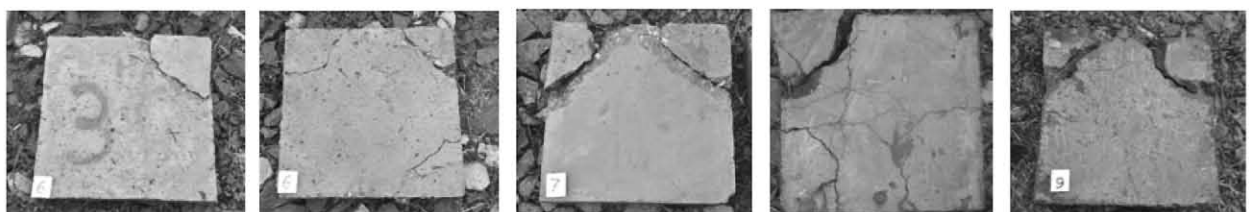


Figure 3. Tested specimens.

Two different material models were used for the simulation of concrete in order to make a comparison between them. The main features of both models are summarized in the next paragraphs, with the most noticeable difference between them being their different level of complexity.

The first material model studied was the Winfrith Concrete model [3] - [5], a smeared crack model specifically developed for modeling concrete behavior, whose main features are:

- (1) Hydrostatic stress state determined through a given compaction curve.
- (2) After failure of an element in tension, a crack is generated in a plane normal to the largest tensile principal stress. Then a crack decay function derived from [18] is set.
- (3) Deviatoric stresses are incremented elastically up to the yield surface defined by Ottosen [19] and given by equation (1).

$$\frac{A \cdot S_2}{\sigma_c^2} + \frac{\lambda \cdot \sqrt{S_2}}{\sigma_c} + \frac{B \cdot J_1}{\sigma_c} - 1 = 0 \quad (1)$$

Where  $S_2$  is the second invariant of stress deviator tensor,  $J_1$  is the first invariant of stress tensor and  $A$ ,  $B$ , and  $\lambda$  are functions of the ratio between tensile and compressive strengths. Coefficient  $\lambda$  also accounts for the parameter  $S_3$  which is the third invariant of stress deviator tensor.

The second material model used is the Brittle Damage model, presented in [20], [21], which is of a much more simple nature than the Winfrith Concrete model. It involves an anisotropic brittle damage smeared crack model in which:

- (1) Compressive behavior is elastic, and although a Von Mises yield criterion can be set, it is not used in the present simulations.
- (2) Tensile behavior is modeled through the formation of smeared cracks on a plane normal to principal tensile stress. A crack stress decay function given by a dissipation law is then used.

Material properties for both models are taken from the compressive strength tests results of 150x300mm cylindrical samples and the predictions given by the Model Code 1990 [22] for such compressive strength (Table 2), except for the fracture energy of concrete, that was estimated as a value of 100 N/m.

Table 2. Mechanical properties for concrete models.

	Density [kg/m <sup>3</sup> ]	Comp. strength [MPa]	Elast. modulus [MPa]	Tensile strength [MPa]
NSC Winfrith model	2500	49.81	38600	4.10
HSC Winfrith model	2500	91.07	46200	6.10
NSC Brit. Dam. model	2500	-	38600	4.10
HSC Brit. Dam. model	2500	-	46200	6.10

### 3.2. Results obtained

Global response of the simulated slab fits those experimentally observed, with a spread cracking on its rear face and re-bounce of the slab due to the elasticity of reinforcing bars.

Cracking pattern predicted by Winfrith model on NSC and HSC (Fig. 4) is mainly of a bending type (cracks forming a cross parallel to the slab sides), although traces of a shear failure mode can be observed on the cracks that surround the supports. On the front face of the slabs, plastic compressive strain is present. A row of plastified concrete elements forms a cross on the front face of the slab, fitting the theoretically predicted behavior by the yield-line method of a four-corner supported slab bending symmetrically under uniformly distributed static loading.

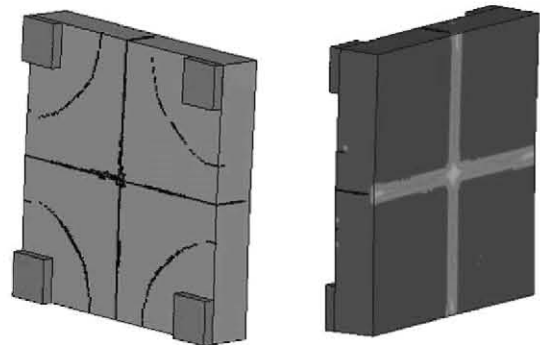


Figure 4. Cracking pattern on slab back side and crushed elements on front face as predicted by Winfrith model.

The existence of a cross formed by crushed elements in the front face simultaneously with a cross formed by cracks on the rear face and beneath the crushed elements, can all be understood as a prediction of a four pieces fracture of the slab, which did not occur in the detonation tests.

In the case of the Brittle Damage model, the failure mode predicted for both concrete types is of a shear kind, more clearly observed in NSC (Fig. 5).

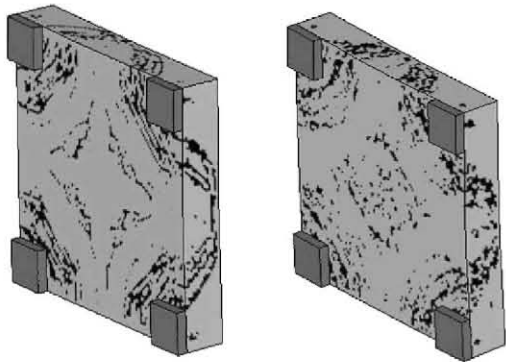


Figure 5. Crack distribution on rear face of NSC (left) and HSC (right) slabs as predicted by the Brittle Damage model.

In contrast with the bending failure predicted by the Winfrith model for NSC, the simpler Brittle Damage model seems to represent in a better way the actual cracking pattern observed in the tests (Fig. 6).

On the simulation of HSC slabs the crack distribution presents a significantly more spread pattern with regard to the modeling of NSC slabs. This response is thought to represent that HSC slabs subjected to the actual blast load present shear failure, though it is not as noticeable as in NSC.

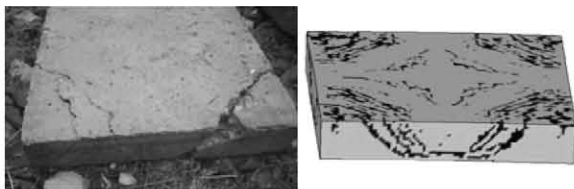


Figure 6. Details of cracking pattern on NSC slabs and prediction of Brittle Damage model.

In order to analyze the structural energy absorption capability of the slabs, the predicted sum of reactions versus central node displacement for both concrete types and both material models are plotted on Fig. 7.

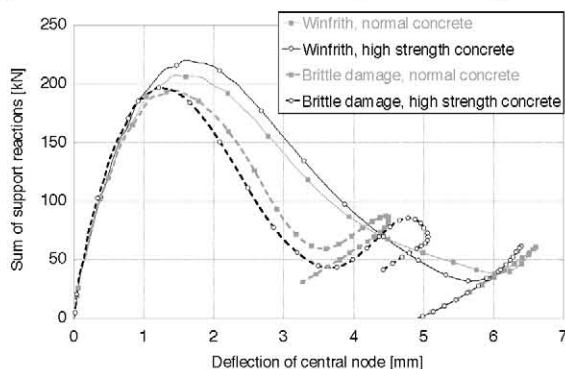


Figure 7. Sum of support reactions versus central node deflection.

With both material models the maximum reaction values are very similar regardless of concrete strength. Such results suggest that for the slab geometry under study, resistance to blast load is governed by tensile strength, which relies on slab reinforcement and is identical for both concrete types. Therefore, compressive strength is thought to play a minor role in the behavior of the slabs presented in this research. These results could also be extended to most structural elements subjected to a blast load, in which the forces acting are primarily tensile.

Moreover, reaction peak values are also similar for both concrete models, despite them being very different models. The reason for this lies in the fact that the main differences between the models is associated with their compressive behavior (much more complex in the Winfrith model), while slab failure is due to tensile stresses.

After the load peak value, the Winfrith model provides a more ductile behavior for both concrete strengths than the Brittle Damage model. As no load-displacement instrumentation was placed in the test, there is no experimental data for checking the predictions from numerical simulations. However, as Brittle Damage gives failure patterns more similar to the experimentally observed, behavior in terms of reactions and displacements should be taken as to be more reliable than that given by the Winfrith model.

#### 4. CONCLUSIONS

In order to provide experimental data for the development and adjustment of numerical tools needed in the modeling of concrete elements subjected to blast, an experimental set-up that allows to test up to four concrete elements simultaneously under the same blast load has been developed.

The results of the experimental program presented suggest that the ability of reinforced concrete structures to withstand blast loads is primarily governed by tensile strength. Therefore, the use of high strength concrete on protective structures may not improve performance remarkably when subjected to a blast load, with a better design procedure being the increase of reinforcement amount.

Numerical simulations were carried out using the LS-DYNA finite element program. For the simulation of concrete behavior, two material models of different complexity were used.

Noteworthy differences between both models lay in their compressive behavior, with them being of a complex nature in one model and very simple in the other. The results obtained with the simpler model seem to be slightly more accurate, supporting the belief that good numerical results can be achieved using simplified material models with suitable cracking and tensile failure criteria.

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