The Influence of the Reinforcement on RC Elements Demolition using Explosives

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Abstract – **This paper proposes a single-degree freedom model to assess the influence of the reinforcement on demolition of the RC beams or columns using explosive charges placed in boreholes. The influence of the reinforcement is computed by quantizing the displacement of the punching cones as a result of detonation. This displacement is influenced by the physical properties of the RC element and explosive. In order to validate the model, experimental tests on RC beams with different geometrical dimensions and amounts of longitudinal and transversal reinforcement have been performed. There were used two types of explosive: trinitrotoluene (TNT) and an explosive mixture based on RDX (EPH), with masses varying between 10 to 50 g. The results show a good proportionality between the size of damage area and the punching cone displacements computed using the model.**

Index Terms **- demolition, contact detonation, reinforced concrete, blast, high explosives.**

I. INTRODUCTION

In controlled demolition of the buildings using explosives, one of the main stages of the design is to determine the amount of the explosive charge needed to explode a discrete portion of the RC element were it is placed. There are different methods of computing this amount of explosive charge that take into account some parameters while others, which can be important enough, are neglected. Thus, Heinze method [1] takes into account the following parameters: type of explosive, material (concrete, reinforced concrete, masonry) and geometrical dimensions of elements, type of effect produced by explosion (fragmentation with loose material or complete demolition) and the place of the borehole. The Berta method [3], which takes into account the influence of the acoustic impedance of the explosive and material, is mainly used to verify the amount of the explosive charges computed with other methods. In his book, Oloffson [3], recommends some specific explosive charge for square drilling pattern. All these methods have the disadvantage that the estimated amount of the explosive charge is oversized and they do not take into account the amount of the longitudinal and transversal reinforcement. The longitudinal reinforcement, but especially the stirrups play an important part in the destruction mode of the reinforced concrete element.

The main goal of the research work was to calculate the reinforcement influence on the RC element exploding during the demolition works using explosives.

In the literature there are few papers on this domain. In their papers, Geib et al [4] and Freund [5] present the results of some experimental and theoretical investigations about the dynamic behavior of a cylindrical concrete vessel under the loadings produced by placing the explosive charges in the boreholes. Numerical simulation and experimentally results exhibits an excellent agreement. Also, numerical simulations of exploding the RC elements phenomenon are presented in [6]. Fujikake et al. [7] performed a qualitatively and quantitatively investigation about the damage of RC columns under demolition blasting. The aim of this study was to apply blasting demolition techniques to RC buildings with excessive reinforcement due to earthquake resistant design.

II. THE MECHANISMS OF RC ELEMENTS DAMAGE USING EXPLOSIVES

There are two typical situations regarding the damaging of the RC element, depending on the position of the explosive charge: charge placed inside, figure 1.a and in contact with an RC element, figure 1.b. The first case corresponds almost totally to the demolition works using explosives, when there are drilling facilities available and time enough to drill blast holes and load them with explosive charges. The second case corresponds to the detonation of the explosive charge in contact with the RC structures, whether it is about the detonation of different caliber ammunitions or demolition due to military or terrorist activities

The failure and damage mechanisms are alike for the two cases of placing the explosive charge. Thus, the most important ones are the cratering and the spalling [8-11]. In the first milliseconds of the detonation process, high-pressure shock waves are transmitted to the element. This fact produces a complete crushing of the material and causes a crater. The shock waves dissipation restricts the area where the material can be crushed although observations on the cross section of concrete elements have shown areas away from the crater where the concrete was crushed. When the shock wave reaches a free surface it is reflected back

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into the element as a tensile wave. If the intensity of the tensile wave exceeds the concrete tensile strength, fractures may be induced in a direction parallel to that of the free surface bringing a bout a possible material removal.

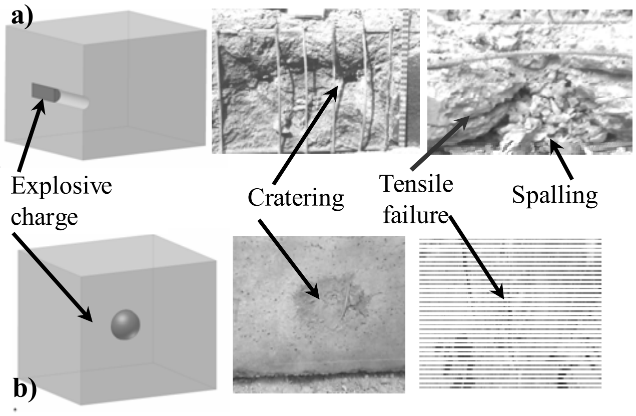


Figure 1 The damage mechanism when the explosive charge is placed a) inside and b) in contact with a RC element

When the explosive charge is placed into the concrete element [11], the action produced by the detonation acts a longer period of time than in case of the contact detonation because of the blasthole confinement. This will bring about a large fragmentation and fracturing next to the crater because of the complex state of the loading that appears at the intersection between the compression waves formed in the explosion area and the rarefaction waves that are reflected by the free surface.

In both cases the damages are mainly influenced by the geometrical dimensions of the RC elements, the amount of the explosive charge, but in case of the charge introduced into the element, the damage level depends significantly on the stirrups and longitudinal reinforcing bars.

III. THE PROPOSED MODEL

The goal of the mathematical proposed model is to make a scenario for the behavior of the RC elements under the detonation of the explosive charge placed into the element in order to determine the influence of the reinforcement on the damage effectiveness.

1. General considerations. Assumptions

The influence of the reinforcement on the effectiveness of the RC element damage is based on a two-degree freedom system with damping [12]. This model was used to evaluate the perforation and bending processes that appear at the impact between a high speed projectile and a RC element by quantizing the displacement of the punching cones that result after the impact.

In this paper a single-degree freedom model was used because, due to the high velocity of the detonation process, only the local response is important and the global action can be neglected.

The displacement of the punching cones is influenced by: i) the mechanical properties of the concrete elements by the concrete tensile strength along the punching cones boundaries, the action of the stirrups elongated after occurring the cracks and the bending of the longitudinal reinforcement when large deformations develop; ii) the properties of the explosive by the detonation velocity and the pressure history variation in time on the blasthole.

The proposed model is based on the following assumptions:

- it was used a beam element with certain dimensions of the cross section;
- the blasthole is drilled into the element for half of the beam depth and its cross section is squared;
- explosive charge shape is a spherical one;
- after the explosive charge detonation, which is placed in the centre of the element cross section, four punching cones will result (figure 2); it is assumed that all explosion energy is used only for propulsion of the punching cones and not for the concrete fragmentation and fracturing;

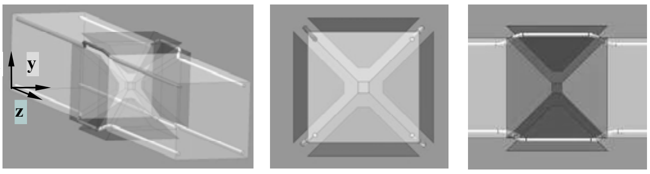


Figure 2 The punching cones formation on RC elements damage using explosive charge placed into blastholes

- the punching cone formation is proper for the local response. The effect of the detonation on general bending of the beam is insignificant and it is not included in the model.

2. Mathematical model

The proposed model (figure 3) is a single-degree freedom model. Its components are: m_{11}, m_{22} - masses of punching cones that occur at the top and bottom of the beam (they are equal and can be named m_1); R_{11}, R_{12}- deformation

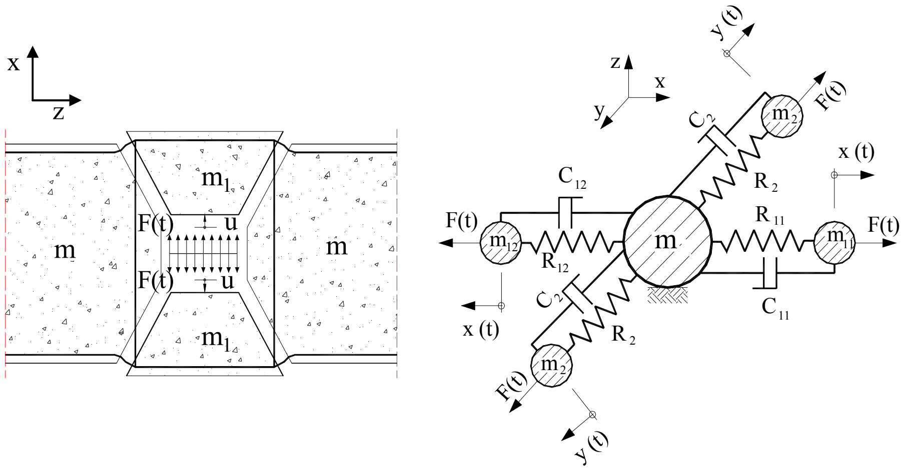


Figure 3 The mechanical model of the detonation into the reinforced concrete beam

characteristics and C_{11}, C_{12} - damping characteristics (these characteristics are different for the top and the bottom parts of the beam based on their different amount of the longitudinal reinforcement); m_2, R_2, C_2 - are mass, deformation and damping characteristics of the punching cones on the lateral beam, *F(t)* force given by the pressure resulted after the detonation producing the displacement *u* of the punching cones; *m* – mass of the beam.

The model gives there independent equations:

$$m_{11}\ddot{x}_1 + C_{11}\dot{x}_1 + R_{11}x_1(t) = F(t) \tag{1}$$

$$m_{12}\ddot{x}_2 + C_{12}\dot{x}_2 + R_{12}x_2(t) = F(t) \tag{2}$$

$$m_2\ddot{y} + C_2\dot{y} + R_2 y(t) = F(t) \tag{3}$$

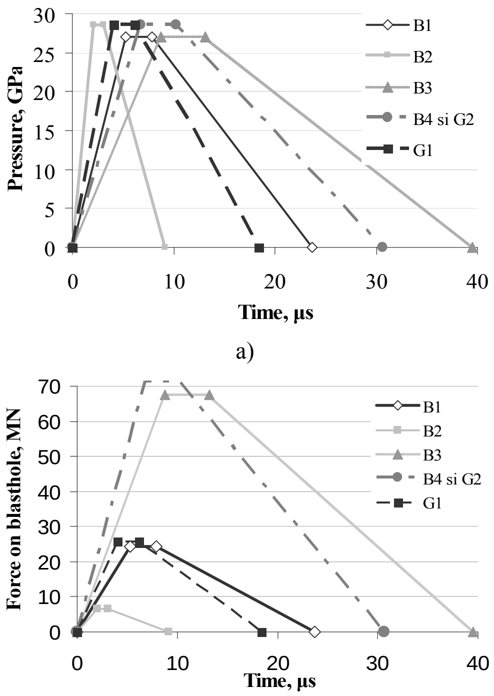
When the amounts of the top and bottom longitudinal reinforcement are equal, there are only two independent equations:

$$m_1\ddot{x} + C_1\dot{x}_1 + R_1 x(t) = F(t) \tag{4}$$

$$m_2\ddot{y} + C_2\dot{y} + R_2 y(t) = F(t) \tag{5}$$

When the dimensions of the cross section are equal (*B* = *H*) and also the longitudinal reinforcement on the top and bottom of the beam are the same, then the model can be described using only an equation that can be either the equation (4) or (5).

The input parameters for the model are: i) the force variation in time on the blastholes; the spring characteristics: ii) nonlinear force-deformation and iii) the damping characteristics; iv) the geometrical dimensions of the elements and of the punching cones.



a)

b)

Figure 4 Pressure a) and force b) history on blastholes

3 History of the force curves determination

The force *F(t)* was computed by multiplication of the detonation pressure *p(t)* with the area of blastholes walls. The area of a blasthole wall was considered the area of a cub face where the explosive charge is inscribed.

In order to determine the pressure history (figure 4.a) the following assumption were made:

- the pressure history was considered to be like that in the domain literature [13, 14] for an explosive charge detonation in contact with a concrete plate;
- the peak of the pressure was considered to be the pressure in front of the shock wave at the contact with the element; it was computed for each type of the explosive using Kamlet-Jacobs method [11];
- the time to maintain the pressure constant level was considered to be double than that obtained from the pressure history from Gebeken et al [13], because in this case the explosive charge is confinement, being introduced in a blasthole.

Based on these assumptions some data were obtained to plot the pressure and the force history on the blastholes (figure 4).

4. *Determination of the force-deformation, the damping characteristics and the mass of the punching cones*

To determine these characteristics the following geometrical model was used, figure 5. The meaning of the notations are: *L* – the beam length between the supports; *H* – the beam height; *B* – the beam depth; *a* – the explosive charge radius; α - the punching cone angle; a_{SB} – amount of the lower reinforcement; a_{ST} – amount of the upper reinforcement; $a_{S\tau}$ - amount of the stirrups

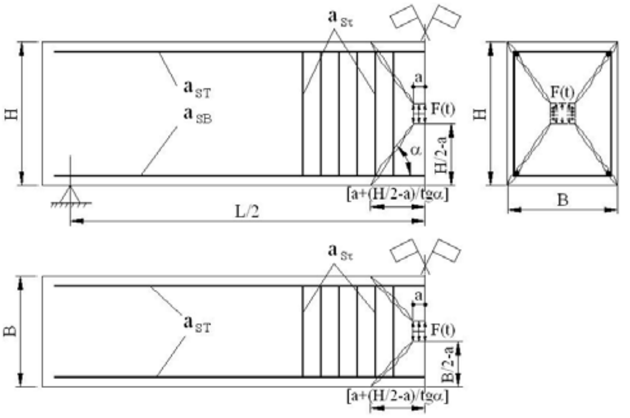


Figure 5 Geometry of the analysed system

Springs stiffness

The nonlinear force – deformation characteristics of the springs are composed of three additive parts: the concrete resistance, the stirrups resistance and the reinforcement bending resistance against punching.

The concrete resistance along the cone boundaries can be computed using the following relation:

$$R_C^u = \left(P_B + P_b\right)\cdot a_p / 2 \cdot f_t \tag{6}$$

where: f_t is the concrete tensile strength; $P_B = 2(B + 2\cdot l_c)$ for the cones propelled on the vertical direction and $P_B = 2(H + 2\cdot l_c)$ for cones propelled on the horizontal direction; $P_b = 8\cdot a$, $a_p = \sqrt{\left(\frac{H}{2} - a\right)^2 + \left(\frac{B}{2} - a\right)^2}$ and $l_c = a + \frac{\frac{H}{2} - a}{tg\alpha}$.

The stirrups elongation resistance is given by the relation:

$$R_S^F = \left(S_B - S_b\right)\cdot \sigma_F \cdot a_{S\tau} \tag{7}$$

where: σ_F is the steel yield stress; S_B is the area of the bottom of the punching cones and $S_b = a^2$ is the area of the top of the cones (in fact the punching cones are truncated

TABLE I THE CHARACTERISTICS OF THE USED ELEMENTS

Element	Dimensions BxH [m]	Concrete strength, f_c/f_t [MPa]	Yield stress for steel, [MPa]	Longitudinal reinforcement			Transversal reinforcement	
				Top	Bottom	ρ_{long}, [%]	Diameter / distance [mm /cm]	ρ_{transv}, [%]
Lintel B1, B2	0.15 x 0.20	12.5/ 0.95	300	2Φ10	2Φ10	1.000	Φ6 / 30	0.126
Lintel B3, B4	0.30 x 0.30			2Φ12	2Φ12	0.502	Φ8 / 25	0.134
Beam G1	0.20 x 0.35			2Φ10	2Φ12	0.548	Φ8 / 10	0.503
Beam G2	0.30 x 0.40			2Φ10	2Φ20	0.655	Φ8 / 10	0.335

pyramid).

The value for S_B is $S_B = B \cdot 2l_c$ for punching cones propelled in vertical direction and $S_B = H \cdot 2l_c$ for horizontal direction.

Reinforcement bending resistance

It is assumed that it has a parabolic tensile membrane behavior [12]:

$$R_B(u,\varepsilon) = 2\sin\left(arctg\frac{4u}{l_c}\right)A_S\sigma(\varepsilon) \qquad (8)$$

where: $\varepsilon(u) = \frac{1}{2}\left[\sqrt{1+\left(\frac{4u}{l_c}\right)^2} + \frac{l_c}{4u}\ln\left(\frac{4u}{l_c} + \sqrt{1+\left(\frac{4u}{l_c}\right)^2}\right)\right] - 1$;

$A_S = l_c \cdot a_S$ and a_S is a_{SB} or a_{ST} depending on the direction of the cones propulsion on the vertical direction or on the amount of the reinforcement on the lateral part.

IV. EXPERIMENTAL INVESTIGATIONS

The main goal of the experimental investigations was to determine the damage mode of the reinforced concrete elements when the explosive charges are placed in the blastholes, figure 6. There were studied the influence of the RC element, the longitudinal and the transversal reinforcements and the type and amount of the explosive.

The RC elements properties used for the experimental investigations are presented in table I.


a) RC elements
b) explosive charge placement
c) clay burden achievement

Figure 6 The main activities performed in order to study the damage of the RC elements using explosive charge placed into the element

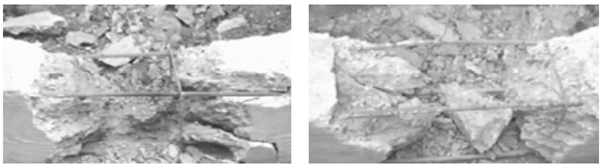
There were used trinitrotoluene (TNT) and an explosive mixture based on hexogen (RDX), with the following properties: a) TNT – density 1415 kg/m^3, detonation velocity - 5700 m/s; b) EPH – density 1650 kg/m^3, detonation velocity - 7160 m/s. The charging parameters are presented in table II.

TABLE II CHARGING PARAMETERS

Element	Explosive	Explosive charge [kg]	Charge diameter [m]
Lintel B1	TNT	0.025	0.030
Lintel B2	EPH	0.010	0.015
Lintel B3	TNT	0.050	0.050
Lintel B4	EPH	0.050	0.050
Beam G1	EPH	0.025	0.030
Beam G2	EPH	0.050	0.050

After the experimental investigations it has resulted that the damages, figure 7, are influenced not only by the dimensions of the RC elements, the type and amount of the explosive, but also by the amount of the stirrups and of the longitudinal reinforcement. The influence of the longitudinal reinforcement can be observed mainly when this amount of reinforcement is considerable (the case of the column in the area where the foundation reinforcement overlap), whereas the influence of the stirrups confinement is very important. Because of the confinement realized by the stirrups, its plane represents a veritable barrier for the crack propagation or for the fragments formation (figure 7.a, 7.b and 7.d).


a) Lintel B1
b) Lintel B2


c) Lintel B3
d) Lintel B4

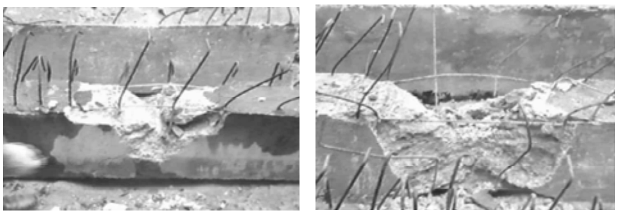

e) Beam G1
f) Beam G2

Figure 7 The destruction mode of RC elements using explosive charge placed inside

The formation of the punching cones is due mainly to the interaction between the shock and the compression waves resulted from the detonation, on the one hand, and to the rarefaction waves resulted from the compression waves reflection by the free surface, on the other hand. The short distances from the explosive charge to the free surfaces and the concrete reduced tensile strength are the main factors which determine the way of column or beam concrete element damage when the explosive charge placed into blastholes are used. The fragmentation and the projection of the displaced and broken material is approximately the same on the free surfaces if the element has equal dimensions for the cross section, which conducts to a pyramidal shape of remained concrete. If the dimensions of the cross section are different then the removal of the concrete is produced on the free surfaces which are closest to the explosive charge, figure 7.c.

In order to quantize the displacement of the punching cones there were represented in figure 8 the length of damage zone, at the blasthole and the reinforcement level, figure 8.a and the deformation of the longitudinal reinforcement, figure 8.b, for both the vertical and the horizontal directions.

V. MODEL APPLICATION

Using the contributions of those three components (concrete, stirrups and longitudinal reinforcement) there were plotted curves for the variation of the force-deformation characteristics for the masses of the punching cones propelled on the vertical direction, figure 9. The analysis of these curves line out some aspects:

- the capacity of concrete to take over the tensile and the shear stresses, on the punching cones boundaries, is greater than the capacity of the stirrups and the longitudinal reinforcement, but can be manifested only for small deformation (maximum 0.0007 cm);
- after the concrete cracking, the stirrups are those that take over the tensile stresses on the concrete shear sections. The deformation range for the stirrups when taking over the stresses is greater than for the concrete, nearly reaching up to 1.3 cm;
- further on, as the deformations increase, the longitudinal reinforcement takes over the stresses produced by the explosion.

VI. RESULTS

After the numerical computing of the equations written down for the RC elements presented in table I, taking into account only the masses propelled on the vertical direction, it resulted the punching cones displacement history, figure 10.a. The following comments can be made:

- the displacements of all punching cones overpass the limit for the concrete cracking, the minimum displacement resulted from the calculations (B2 element) is 0.11 cm and it is greater than the deformation corresponding to the concrete cracking (0.0007 cm, figure 9);
- the association between the displacement of the punching cones and the length of damaged zone, that is the reinforcement bending, can be easily followed-up if the ratio between the distance from the explosive charge to the free surface and the burden, - the TNT equivalent of explosive charge - is graphically plotted, figure 10.b. The bigger this ratio is the smaller the punching cone displacement. Thus, we can explain why for the RC elements almost identical from the geometrical configuration and reinforcement point of view (elements B1 and B2, respectively B3 and B4), differences occur regarding the length of the damaged zone and the longitudinal reinforcement bending.

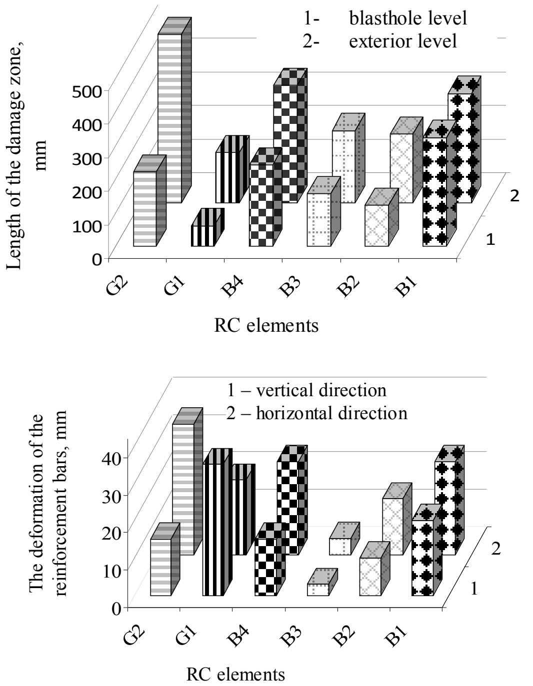


Figure 8 The length of the damaged zone and the deformation of the reinforcement bars

- for example, the B4 and G2 elements have almost the same dimensions for their cross sections (0.3 x 0.3 m for B4 and 0.3 x 0.4 m for G2) and explosives of the same type and mass (50 g EPH) were used; in these conditions the differences among the punching cones displacement curves are exclusively given by the differences between the quantities of the stirrups and the longitudinal reinforcements. Thus the maximum displacement of the punching cones for the G2 element is 35% (5.5 mm) smaller than the maximum displacement of the B4 element and corresponds to a difference of 30.5% for the longitudinal reinforcement and 149 % for the stirrups between the two elements.

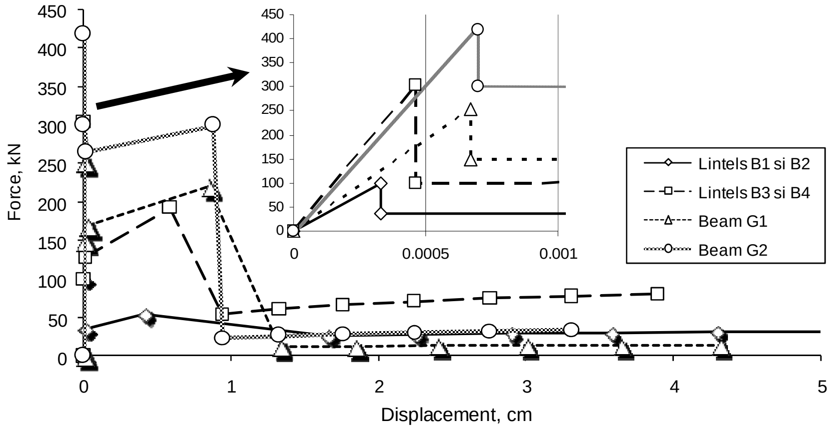
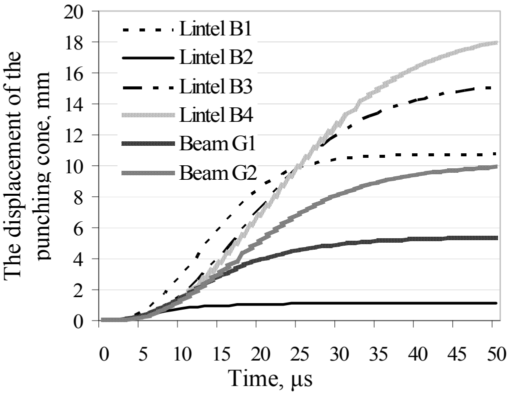
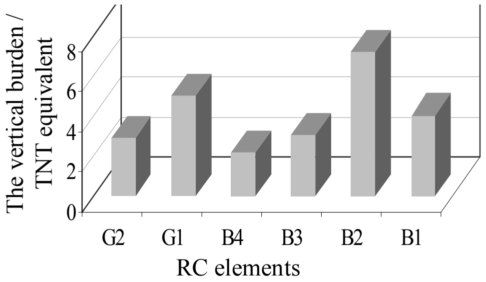


Figure 9 Spring characteristics for the punching cones propelled in the vertical direction



a)The displacement of the punching cone vs. time



b) The ratio between the vertical burden and TNT equivalent

Figure 10 The model assesment

VII. CONCLUSIONS

While there are some methods for computing the drilling and charging parameters for the reinforced concrete elements exploding, it is necessary to take into consideration the knowledge and to explore of phenomenon that takes place at the explosive charge-concrete element interaction especially in terms of the influence of the amount and placement of the longitudinal and transversal reinforcement on the element damage, in order to optimize these methods.

In this respect, a single-degree freedom model was developed in order to determine the influence of the reinforcement on the effectiveness of the element damage by quantizing the punching cones displacements resulting after the explosive charge detonation. The displacements of the punching cones are influenced by the mechanical properties of the concrete elements and the properties of the explosive charge. Taking into account that the loadings produced by the explosion are impulsive loadings then the pressure history and not the peak value was taken into consideration when determining the force on blastholes history.

The model application has a series of advantages: i) it takes into account the amount of the longitudinal reinforcement; ii) it considers the number and the distance among the stirrups; iii) it has in view the type and amount of the explosive charge used to destroy the RC element. The results – largely presented and commented in the previous chapter- showed that there is a good proportionality between the displacement of the punching cones and the size of the damage areas.

In order to use the proposed model for computing the explosive charge necessary to demolish an RC element, research is needed to determine the correlation between the value of the punching cone displacement and the level of the element damage. This can be obtained by making experimental investigations for different reinforcement configurations and masses of the explosive charges in order to measure the size of the damaged and cracked zones and also the deformation of the longitudinal reinforcement. These values will be compared with the punching cones displacements and the result of these comparisons will be a coefficient that can be used to improve the existing relations to compute the drilling and the charging parameters for the RC element demolition using explosions.

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